Recoupling the Livestock Nutrient Economy: A Path forward for Water Quality Improvement

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Intensification of farming operations and increased nutrient application rates have led to higher crop yields and greater food security. At the same time, widespread use of commercial nitrogen (N) and phosphorus (P) fertilizers and large-scale livestock production have led to unintended environmental consequences, including eutrophication of both coastal and inland waters, threats to drinking water, and increased production of N_2O, a potent greenhouse gas.

In the past, crop and livestock production were typically more integrated, allowing most livestock to be fed by local crops, and most livestock manure to be applied directly to nearby cropland. Under current intensive agriculture practices, however, there is frequently a spatial decoupling of crops and livestock, leading to hot spots of manure production and a lack of opportunities for cost-efficient and environmentally sensitive disposal. In recent years, there has also been increased interest in the use of both farm and regional-scale bioreactors to convert excess manure to energy, thus exploiting a renewable energy source and increasing the potential to recycle animal waste.

In the present work, I develop a spatially distributed optimization approach to identify hotspots of manure production, and, using both economic and environmental criteria, evaluate the economic feasibility of (1) transporting manure for spreading on cropland to meet established nutrient requirements, and (2) constructing biogas reactors to process excess manure in areas where long-range transport is found to be infeasible. This work is focused on manure redistribution, and potential for biogas construction at the continental US scale.

In order to identify the spatial disconnect between livestock and crop production, I developed a gridded data set where each cell was 6 km x 6 km and calculated the crop requirements and

manure production in each cell. After finding the P requirements in each cell, I found that 530,000 tonnes of phosphorus in manure was located in areas where, if applied, it would be in excess of the local crop requirements.

I then examined the feasibility of transporting manure from excess locations (cells) to other locations to use as fertilizer by formulating an optimization problem to maximize the financial benefits of transporting the manure. Savings from transporting manure was calculated as the financial benefit from buying less mineral fertilizer minus the cost of transporting the manure. The solution to this optimization problem shows that transporting manure was able to reduce the excess phosphorus applied to fields by at least 88% with savings of up to $3 billion USD.

Finally, I examined the costs and benefits of using the remaining excess manure (after transportation for fertilizer) as fuel to operate biogas plants. For this, I formulated an optimization model to site biogas plants across the continental US such that net profits from the biogas plants were maximized. Biogas net profits were defined as the money made from selling electricity minus the annualized costs for constructing and operating the biogas plants and transporting the manure to the biogas plants. The solution to this problem shows that constructing and operating 387 biogas plants yielded a net profit of $100 million USD and would utilize all of the manure remaining after transportation for fertilizer. This 100% utilization rate of excess manure would have great environmental benefits in terms of removing potential sources of non-point source pollution from farms that would otherwise be available to runoff into waterways.

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Chapter 1 – Introduction

Increases in global population and per-capita food consumption have greatly increased agricultural demand worldwide (Garnett et al., 2013; Godfray et al., 2010). These increases in agricultural demand have been accompanied by increases in the nitrogen and phosphorus loading into the environment (Hashemi et al., 2016). Nutrient loading from agricultural runoff has been linked to harmful eutrophication in lakes, estuaries, and marine environments (Boesch, 2002; Hagy et al., 2004; Schindler, 1974). Increasing nutrient controls have been found to be effective at controlling algae growth and preventing eutrophication (Carpenter, 2008; Robert W. Howarth & Marino, 2006; Schindler, 1974; Schindler et al., 2008), but record-setting algae blooms are still occurring in Lake Erie and the Gulf of Mexico (Conley et al., 2009; R W Howarth, 2005; Lewis et al., 2011; Van Meter et al., 2018; Michalak et al., 2013).

One of the major sources of nutrient runoff from agriculture is from manure in animal feeding operations (Anderson et al., 2002; R.W. Howarth et al., 2002; Lewis et al., 2011). Livestock production in the United States has seen a shift from small farms to larger concentrated animal feeding operations (CAFOs) over the last 60 years (Kellogg et al., 2000; Mallin & Cahoon, 2003). CAFOs often apply excess manure nutrients to cropland, underestimate the amount of land needed for manure nutrients, and overestimate crop requirements (Kellogg et al., 2000; Long et al., 2018). This application of excess nutrients can result in a build-up of nutrients within the soil and lead to significant nutrient runoff during rain events (Centner, 2011; Mallin & Cahoon, 2003; Motew et al., 2018).

The increases in agricultural demand have also led to increasing trends in mineral fertilizer use that is expected to continue into the future (Bouwman et al., 2013; Godfray et al., 2010; Tilman et al., 2011). The increase in demand for mineral phosphorus has also led to increased concerns about the increasing scarcity of phosphorus rock (Cordell et al., 2009; Gilbert, 2009). As the demand for phosphorus fertilizer rises and the supply decreases, the price of mineral phosphorus is expected to rise (Koppelaar & Weikard, 2013; Sverdrup & Ragnarsdottir, 2011; Van Vuuren et al., 2010) Concerns about the supply of mineral phosphorus and of food security have led to an increased focus on a sustainable phosphorus cycle (Cordell & White, 2013; Koppelaar & Weikard, 2013). This process includes the effective reuse of manure as a phosphorus source for crop fertilizer (Childers et al., 2011; Jurgilevich et al., 2016). Countrywide, phosphorus in manure may be able to meet a significant fraction of the annual crop demand (MacDonald et al., 2012; Mueller et al., 2012), but much of this manure is over applied near its source to merely dispose the excess (Long et al., 2018; Schröder et al., 2011). This overapplication of manure leads to increased inputs of the nutrients into the environment (Centner, 2011). In order to effectively meet the crop demand, it is possible to transport manure from excess to deficit locations (Metson et al., 2015). However, there are obstacles to transporting manure and using it as fertilizer. Some farmers are reluctant to use manure as fertilizer for a variety of reason including health risks and uncertainty about the nutrient content of the manure (Long et al., 2018). Also, the ability to transport manure in a cost-effective way is dependent on the livestock that produced the manure and the cost of mineral fertilizers. This distance can vary from as low as 15 km to over 400 km depending on the source of the manure (Keplinger & Hauck, 2006; Paudel et al., 2009; Sharpley et al., 2016).

An alternative to directly applying manure as fertilizer while still improving phosphorus recycling is through the use of biogas plants (Angelidaki & Ellegaard, 2003; Lantz et al., 2007; White et al., 2011). Biogas plants use manure or other organic material to generate biogas through anaerobic digestion, reducing the GHG emissions from manure (Cuéllar & Webber, 2008; El-Mashad & Zhang, 2010). The biogas produced can then be used to generate electricity and produces phosphorus rich by-products (Cuéllar & Webber, 2008; Massé et al., 2011). The by-product of anaerobic digestion also can be used as fertilizer and has some benefits over direct manure application such as decreased risk of pathogen spread and an increase in available phosphorus (Insam et al., 2015). Despite these benefits, biogas operations using manure are not common, with less than 300 of them operational in the United States in 2016 (AgSTAR, 2016) with the majority of these as small biogas plants. This is despite the findings that biogas plants have also been found to have a positive economy of scale, allowing larger centralized plants to be more cost efficient than smaller ones (AgSTAR, 2016; Ghafoori & Flynn, 2007; Lantz, 2012).

1.1 Objectives

This work develops a spatially distributed model to identify hotspots of manure production throughout the U.S., and, using both economic and environmental criteria, will evaluate the feasibility of (1) transporting manure for spreading on cropland to meet established nutrient requirements, and (2) constructing biogas reactors to process excess manure in areas where long-range transport is found to be economically infeasible. Although many assessments of the benefits of biogas reactors consider only benefits with regard to reductions in GHG emissions, this work will explicitly incorporate benefits to water quality into our economic and environment criteria. My overall hypothesis is that there is currently a significant spatial disconnect across the United States between manure production and nutrient requirement areas. I also hypothesize that it is possible for locations with excess manure to use this manure in a cost-effective manner through manure transportation for fertilizer use and through the construction of biogas plants that use manure as fuel. The specific objectives are:

1) Build a grid-scale phosphorus balance between crop phosphorous demand and manure phosphorous production for the United States.
2) Develop a framework to estimate the costs and benefits of manure transport
    a. Examine the costs and benefits of manure transport in order to meet the crop phosphorous demand.
    b. Optimize the transport in order to maximize the benefits from manure transportation.
3) Develop a framework to estimate the costs and benefits of biogas plants using manure as fuel

a. Examine the costs and benefits of building and operating biogas plants in order to reduce excess phosphorous
b. Optimize the locations of biogas plants in order to maximize the benefits and minimize the costs.

In Chapter 2, the current literature related to manure management and optimizing manure usage is presented and gaps in the literature are identified. Chapter 3 presents the methods used in data synthesis, algorithm development, and optimization problem formulation. In Chapter 4 my results of the analysis and model development are presented and discussed. Chapter 5 summarizes the results and discusses future directions for this work.

Chapter 2 – Literature Review

This chapter describes existing literature about manure management (Section 2.1) and optimization methods for manure management (Section 2.2), then addresses gaps in the existing literature (Section 2.3).

2.1 Manure Transportation Studies

Multiple studies examine the possibility of increased manure recycling at a national or global scale with regards to the ability of the manure to meet the nutrient demand of crops (Bateman et al., 2011; Bouwman et al., 2013; MacDonald et al., 2012; Metson et al., 2015; Sheldrick et al., 2003). Bouwman et al. (2013) and Sheldrick et al. (2003) both estimate phosphorus balances across the globe, but do not examine any methods of phosphorus recycling or the costs associated with doing so. MacDonald et al. (2012) estimated phosphorus demands in the United States and found that changes in farm management, including increased phosphorus recycling, could reduce phosphorus fertilizer requirements in the United States by half.

Metson et al. (2015) estimated that 37% of phosphorus from livestock manure and human waste would be needed in order to meet the phosphorus required for corn harvested in the United States. They then focused on the corn belt, a collection of 13 states that they found contributed 84% of the national phosphorus demand from corn. They found that meeting the corn phosphorus demand within the corn belt through recycling phosphorus from livestock manure and human waste would require phosphorus from counties up to 132 km away and would require transporting manure between 65 and 519 km. However, this study did not calculate the costs associated with the phosphorus recycling and just estimated the transport distances necessary.

Bateman et al. (2011) evaluated the phosphorus balance in the UK and found that there were two regions with phosphorus surpluses and six regions with phosphorus deficits. The livestock manure in the UK was estimated to be able to meet 71% of the crop phosphorus requirements in England, reducing the amount of mineral fertilizer required. This study also examined the temporal phosphorus demand at time scales shorter than a year and found that using livestock manure to meet phosphorus requirements would require the storage of 15 million tonnes of manure for use in March and later in the year. They did not calculate distances that manure would need to be transported or costs for either transportation or storage.

Another method of using livestock manure when using it for fertilizer is undesirable is as fuel for a biogas plant. There are multiple studies that examine the costs and benefits of operating biogas plants using livestock manure as fuel, but these studies are often focused on the farm scale costs and benefits (Bachmaier et al., 2010; Fuchsz & Kohlheb, 2015; Ghafoori & Flynn, 2007; Hamelin et al., 2014; Ishikawa et al., 2006; Lantz, 2012; White et al., 2011). However, studies that examine the national benefits of biogas plants are less common. Cuellar & Webber (2008) estimated that using manure in biogas plants could supply the US with 2.4% of the total annual energy requirement when using the generated biogas to operate turbines. Additionally, this reduction in power would reduce the US annual GHG emissions by 99 million metric tons (3.9% of annual emissions) by reducing manure GHG emissions and reducing the amount of coal energy required.

2.2 Manure management through optimization methods

In addition to the studies already discussed, a number of studies used formal mathematical optimization methods to implement manure management strategies in order to minimize management costs. Table 1 shows optimization studies about manure management. The majority of these studies focused on transporting manure for use as fertilizer, two of the studies looked at general farm management including manure fertilizer application, and one study looked at maximizing the profits of running biogas plants with livestock manure as fuel. Four of the studies were done at the national scale. Of these studies, two of them focused on the United States (Kaplan et al., 2004; Keplinger & Hauck, 2006), one looked at Sweden (Akram, Quttineh, Wennergren,

Table 1. Optimization studies related to transporting manure or locating biogas plants.

Authors	Problem Type	Application	Objectives	# of Types of Variables	# of Types of Constraints	Scale
(Akram, Quttineh, Wennergren, & Tonderski, 2019b)	Linear	Manure transportation	Manure transport costs	1	3	National
(Akram, Quttineh, Wennergren, Tonderski, et al., 2019a)	Linear	Manure Transportation	Manure transportation costs	1	8	National
(Kaplan et al., 2004)	Linear	Manure transportation	Profits for livestock operations	1	1	National
(Keplinger & Hauck, 2006)	Linear	Manure transportation	Manure application costs	2	3	National
(Sharara et al., 2017a)	Linear	Manure transportation	Manure application, manure transport costs	1	6	Sub-watershed
(Biberacher et al., 2009)	Linear	Manure transportation	Manure transport costs	3	3	Multi-district
(Giasson et al., 2014)	Linear	Manure transportation	P losses, standard deviation of P losses across farms, costs	3	10	Farm
(Groot et al., 2012)	Non-linear	Farm management	Farm profit, labor requirements, organic matter	3	7	Farm
(Liang & Cabrera, 2015)	Non-linear	Dairy productivity	Milk production	-	-	Farm
(Park et al., 2019)	MILP	Biogas plant location	Total costs, carbon emissions	5	10	State

Tonderski, et al., 2019), and one looked at Sweden and Pakistan (Akram, Quttineh, Wennergren, & Tonderski, 2019).

Keplinger & Hauck (2006) evaluated the costs and benefits of transporting livestock manure from various sources. They then minimized the costs of applying manure and fertilizer to the land under different environmental policies. These policies affected how much of the manure must be spread and the location where it was to be spread (the two types of decision variables). They solved their linear optimization problem and found that requiring manure to be spread when limiting phosphorus application resulted in significant negative benefits from moving manure and higher costs when moving manure with low phosphorus content.

Kaplan et al. (2004) examined the effect of implementing policies to constrain the nutrient inputs from manure on cropland to crop production requirements. They maximized the profits from livestock operations under nutrient constraints. They then used the U.S. Regional Agricultural Sector Mathematical Programming Model (House et al., 1999) to provide constraints, crop, and livestock information. They estimated that losses from meeting nutrient constraints could reach $830 million, potentially resulting in price increases for consumers. The most affected regions of the United States would be the Appalachia, Pacific, and Southeast regions due to the higher livestock population relative to cropland than other regions.

Akram et al. (2019a) calculated the phosphorus balance in Sweden and then found the amount of manure that would need to be transported in order to meet P and NPK limits. They optimized for cost under two different sets of constraints. The first set of constraints was for transportation in order to eliminate P excess, while the second set was for transportation in order to eliminate NPK excess. They calculated the phosphorus balance at for each municipality and kept that resolution for the optimization models. When meeting P requirements, they found that the average travel distance between the surplus and deficit location was 202 km and that the cost of transporting the manure would be 3.7 times higher than the value of the NPK fertilizer that it would replace. This transportation was estimated to reduce fertilizer requirements by 34% for N and 48% for P.

Akram et al. (2019b) has also found that the data resolution affected the results when calculating required transport distances. Compared to using political boundaries, decreasing the spatial resolution to 5 km increased the amount of nutrients requiring transport but decreased the mean transport distance in both Pakistan and Sweden. Decreasing the resolution also decreased the cost to value ratio, allowing manure transport to appear more beneficial when working with smaller resolutions.

Park et al. (2019) formulated two mixed integer linear programming (MILP) model to optimize new biogas plant locations within the state of North Dakota in a way that either minimized the total costs associated with the biogas plants or minimized carbon emissions. They identified 22 potential biogas locations based off of land use and other geographic criteria, then optimized for both of the objectives. They found that costs and carbon emissions are conflicting objectives, where costs increased as emissions decreased. Of the 22 selected potential sites, the solution that minimized the cost selected 9 of the potential sites for a biogas plant while the solution that minimized for emissions selected 20 of the sites.

2.3 Gaps in Literature

Research in manure management has examined the crop phosphorus requirements and compared them to manure phosphorus available in the United States and in other countries worldwide. However, this analysis is rarely done for resolutions higher than the county scale or equivalent. Higher resolution analysis (e.g., 5km by 5 km resolution) was done by Akram et al. (2019b) for Sweden and Pakistan, but has not been done for the United States. The most detailed work in the US is found in Kaplan who optimized manure transport at the regional and subregional scales. My first objective will address this and will create a phosphorus balance between crop requirements and manure supply in the United States at a subcounty scale (6 km by 6 km grids) .

Of the numerous studies that examined the possibility of transporting manure relatively few of these studies have investigated how to formally optimize the redistribution of manure and even fewer have considered the economic benefits and costs of such redistribution (Akram, Quttineh, Wennergren, & Tonderski, 2019a; Akram, Quttineh, Wennergren, Tonderski, et al., 2019b; Kaplan et al., 2004). Of these few studies, the most relevant US national scale study examining optimal redistribution for fertilizer is the Kaplan et al. (2006) study. However, their resolution is too coarse and their analysis uses 2002 fertilizer costs which have now nearly tripled. Both shortcomings result in an underestimation of the net economic benefits of redistributing manure for fertilizer. My work provides an important up to date optimization analysis to better estimate current day economic benefits of manure redistribution at the continental US scale.

Some of the previously described studies analyzed the ability to use manure in place of fertilizer, but never with the operation of biogas plants presented alongside it as an option. The ability of biogas plants to utilize excess manure across the country has been explored by Cuellar & Webber (2008), but no detailed analysis on cost or optimal plant locations has been done. This study aims to fill these gaps by examining the combined costs and benefits of both manure redistribution for fertilizer and the use of manure in biogas plants. This combined analysis is done sequentially (optimally redistribute manure for fertilizer and then optimally site biogas plants considering remaining excess manure) for the continental US and then done sequentially and simultaneously for the state of California.

Chapter 3 – Methods

This chapter describes in detail the methods used to develop a grid-scale P balance (Section 3.1), the cost benefit calculations associated with transporting manure (Section 3.2), and the methods used to formulate and solve the various manure redistribution optimization models (Sections 3.3 and 3.4). The grid-scale P balance data and the cost calculations form the critical inputs needed for the optimization models. All required datasets and assumptions for both the grid-scale P balance and the optimization models are described in detail in this chapter.

3.1 Grid Scale P Balance

I first built a gridded data set showing the difference between crop P requirements and manure P generated across the Contiguous United States (CONUS) at the 6 km x 6 km grid scale. A 6 km x 6 km grid was selected to balance spatial resolution goals, raw input data resolution availability and computer processing requirements. Note that I focused on 2012, the most recent year for which data was available. In this section, I describe the methodology to build this gridded dataset.

The gridded P balance was derived by calculating two values, crop P uptake and manure P production, by combining various spatial datasets with a number of assumptions. Crop P uptake is the amount of phosphorus that crops in a grid cell require each year in order to properly grow. Manure P production is the amount of phosphorus contained in manure collected from livestock in a cell each year. The required datasets are listed below in Table 2. All datasets in Table 2 are from 2012 except for the datasets for livestock density, livestock manure production, and manure collection rates. The livestock density dataset is for the year 2005, the livestock manure production dataset is for the year 2002, and the manure collection dataset is for the year 2000. These datasets were assumed to have not significantly changed between the year they were collected and 2012. While some location changes may have occurred between 2005 and 2012, using the 2012 census data for the population allowed the populations within each county to be accurate. There may be some changes in location that was missed by using 2005 data to determine livestock locations, but this was considered preferable to restricting the analysis to the county level.

Table 2. Data Sources for P data set utilized to compute Net P inputs for the year 2012.

Data Used	Units	Data Resolution	Data Year	Data Source
Livestock Populations	Head	County/State	2012	USDA Census
Crop P Uptake	ton P/county	County	2012	(IPNI, 2012)
Land Use	Categorical	20m x 20m Gridded	2012	(USDA NASS, 2012)
Livestock Density	head/square km	1km x 1km Gridded	2005	(Wint & Robinson, 2007)
Livestock P production rates	kg P/head/year	Constant	-	(Russel et al., 2008)
Livestock manure characteristics	lb P/ton manure	Constant	-	(North Carolina Agricultural Chemicals Manual, 2002)
Manure collection rates	Percentage	State	2000	(Kellog et al., 2000)

Calculating the P balance was a six step process. The first step was building the gridded data set used for the analysis. This was done by dividing the contiguous United States into a regular grid where each cell was 6 km by 6 km. After creating grid cells, the second step was defining the land use for each cell. This was done by assigning each 6x6 km cell the most dominant land-use value within its boundary from the USDA NASS Cropland Data Layer. Each cell was thus classified as agricultural cropland, agricultural non-cropland, or non-agricultural. Third, Crop P uptake was calculated in each cell using the NUGIS dataset that provides information on the crop P uptake at the county scale (IPNI, 2012). The crop P uptake for each county was evenly divided between all the cells within the county that were previously classified as agricultural cropland. This assumed that there was not a significant difference in crop uptake between different cells within a county.

Fourth, manure P production was calculated for each 6 km x 6 km grid cell using the livestock population census data available at the county scale (USDA-NASS, 2012), and the livestock density dataset available at the 1 km x 1km grid scale (Wint & Robinson, 2007). Seven livestock types were used for this calculation: beef cows, milk cows, cattle, hogs, broiler chickens, layer chickens, and roosters. Livestock were assumed to be present in any cell within a county classified as either agricultural cropland or agricultural non-cropland. This resulting in livestock being present in cells that were originally considered cropland, rangeland, and pastureland. The livestock density data set [heads per square km], available at the 1 km x 1 km scale, was upscaled to the 6 km x 6 km grid by aggregating the finer scale information. This information was only available for 2005. To obtain grid-scale livestock numbers for 2012, I proportioned 2012 county-scale livestock numbers to the grid-scale by assuming that the proportion of the county's livestock that are in grid cell i is constant across years, using the livestock data as weights to distribute the county-scale values to the grid-scale. This was repeated for each county and each type of livestock. The population data in some counties was unavailable due to privacy concerns. When the county level population data was unavailable, state population data was used instead. When state data livestock population data needed to be used, the livestock populations of the counties with known populations was subtracted from the state total before proportioning the remaining population across all grid cells in counties without population data.

Fifth, after finding the livestock population in each grid cell, the P production was calculated. First, grid cells with population small enough that no collection would occur were set to a P production of 0 tons/year. The limits used for this were defined by Kellog et al. (2000) as the minimum livestock population a farm would require before manure collection occurs. The P production of the cells with larger populations was calculated by multiplying the population by the annual P production and the manure collection rate (Kellogg et al., 2000). The manure collection rate is the fraction of the manure that is able to be collected and is dependent on the location of the livestock, the type of livestock, and the size of the farm. Kellog et al. (2000) first identified the minimum farm size necessary for livestock manure to be collected, then identified a fraction of manure collected for each combination of state and livestock type. These values were collected and a value was assigned to each cell based on the location and the population of each livestock. After doing so, the equation for the phosphorus production in each cell was:

$$P_{i,j} = H_{i,j} * r_{p,j} * r_{c,i,j}; \ \forall\, i, j \tag{1}$$

where $P_{i,j}$ is the phosphorus produced by the livestock j in grid cell *i* [tons], $H_{i,j}$ is the population of livestock j in grid cell *i* [head], $r_{p,j}$ is the annual phosphorus production rate of livestock j [tons/head], and $r_{c,i,j}$ is the collection rate of manure for livestock j in grid cell i. After finding the phosphorus production of each type of livestock in each grid cell, the total manure P production in each grid cell was calculated by summing the production from each type of livestock.

Last, after estimating the manure P production and crop P uptake in each grid cell, a P balance was created by subtracting the crop P uptake from the manure P production. This resulted in a gridded data set where cells with positive P values had more P than crops needed (excess P) and cells with negative P values had less P than crops in the cell needed (deficit P).

3.2 Estimation of Cost Savings Associated with Manure Distribution and Biogas Plants

The excess P in manure estimated at the grid scale can be either redistributed to meet fertilizer needs of grid cells where there is a P deficit or transported to biogas plants for electricity generation. Here, I develop the equations to estimate the savings associated with each of these scenarios as a function of the (i) manure transportation costs and (ii) fertilizer benefits.

For both objectives, the savings was calculated subtracting costs from benefits. The costs, benefits, and savings for manure redistribution are defined and calculated in Section 3.2.1. The costs, benefits, and savings for the construction and operation of biogas plants are then defined and calculated in Section 3.2.2.

The required data for the costs calculations are listed below in Table 2. All datasets in Table 2 are from 2012 except for the datasets for truck transportation costs, biogas plant costs, and biogas plant efficiency. The truck transportation costs and biogas costs were adjusted for inflation to 2012 and were assumed to have not significantly otherwise changed since their publishing. The biogas plant efficiency was also assumed to have not significantly changed between when it was published and 2012.

Table 3. Data sources for manure distribution and biogas plant construction costs for the year 2012.

Data Used	Symbol	Value	Units	Data Year	Data Source
Fixed truck transport costs	C_f	Variable	USD/ton manure	2007	(Ghafoori et al., 2007)
Variable truck transport costs	C_v	Variable	USD/ton manure/km	2012	(Ghafoori et al., 2007)
Cost of ammonium nitrate fertilizer	C_{PF}	506	USD	2012	(USDA NASS, 2012)
Cost of superphosphate fertilizer	C_{NF}	665	USD	2012	(USDA NASS, 2012)
N mass in ammonium nitrate fertilizer	N_F	0.35	ton N/ton fertilizer	2012	(USDA NASS, 2012)
P mass in superphosphate fertilizer	P_F	0.15	ton P/ton fertilizer	2012	(USDA NASS, 2012)
Biogas plant fixed costs	c_0	19466	USD	2013	(ICF International, 2013)
Biogas plant variable costs	c_1	10.55	USD/ton manure	2013	(ICF International, 2013)
Value of electricity	l_1	2.9*10E-05	USD/Btu	2012	(U.S. Energy Information Administration, 2012)
Energy production rate	r	35703	Btu/m3 methane	-	("Fuel Gases Heating Values," n.d.)
Biogas production rate	b	21	m3 methane/ton manure	2013	(ICF International, 2013)
Electricity production efficiency	η	0.85	-	2013	(ICF International, 2013)

3.2.1 Manure Distribution Savings

Manure redistribution savings can be defined as the difference between the cost of transporting manure and the cost of the fertilizer that the transported manure would replace. I first calculated the local savings for a single trip from an excess cell *i* to a deficit cell *j*, and then summed savings from all possible trips to estimate the system wide savings. The cost of each trip was calculated using costs from Ghafoori et al. (2007) and the manure was considered to be able to be transported as either a slurry or a solid. The fixed and variable costs associated with transportation as a slurry or as dry manure are different and it was assumed that the less expensive of the two methods would be used as transportation from each grid cell. The costs for each type of transportation are shown in Table 2. These costs were made assuming the use of 30- and 40-ton trucks for transportation.

Table 4. Fixed and variable costs of truck transportation of manure[1].

Transportation Method	Fixed Cost [$/ton manure]	Variable Cost [$/ton manure/km]
Dry	7.76	0.105
Slurry	2.59	0.247

[1] Adjusted to 2012 USD.

The benefits of transporting the manure was defined as the cost of the fertilizer that the manure transported would replace at the destination cell. The cost of the fertilizer was calculated using USDA NASS data for the cost of superphosphate and ammonium nitrate fertilizer for 2012.

The unit savings from transportation during each trip (c_{ij} ; $/ton P) was calculated as the savings associated with not applying P fertilizer (C_{PF} /P_F; C_{PF} is the cost of superphosphate fertilizer [$/ton fertilizer] and P_F is the phosphorus mass fraction in superphosphate [ton P/ton fertilizer]), plus the savings associated with not applying N fertilizer ((C_{NF}/N_F)*($N_{M,i}$/$P_{M,i}$); C_{NF} is the cost of ammonium nitrate fertilizer [$/ton fertilizer]; N_F is the nitrogen mass fraction in ammonium nitrate fertilizer [ton N/ton fertilizer], $P_{M,i}$ is the phosphorus mass fraction in the manure at cell i [ton P/ton manure], $N_{M,i}$ is the nitrogen mass fraction in the manure at cell i [ton N/ton manure]) minus the cost of transporting manure (third term on the RHS in Equation 2), as described by the following equation:

$$c_{ij} = \left[\frac{C_{PF}}{P_F} + \frac{C_{NF}}{N_F} * \frac{N_{M,i}}{P_{M,i}} - \frac{C_f + C_v * d_{ij}}{P_{M,i}}\right] \tag{2}$$

where c_{ij} is the unit savings when transporting manure from cell i to cell j [$/ton P], C_f is the fixed cost of transporting manure [$/ton manure], C_v is the variable cost of transporting the manure [$/ton manure/km], and d_{ij} is the distance between cells i and j [km].

In this equation, the benefits from transportation are the C_{PF} and C_{NF} terms. They are then converted from savings per ton of fertilizer to savings per ton on P transported. The fixed and variable costs of transportation are the C_f and C_v terms. These are converted from the cost per ton M values in Table 2 to a cost per ton of phosphorus transported by multiplying the cost per ton by the phosphorus mass fraction in the manure in each cell i. The unit savings for each trip are then calculated by adding the savings from not having to purchase P fertilizer [$/ton P] and the savings associated with not having to purchase N fertilizer [$/ton P] together and subtracting the cost of transporting manure [$/ton P].

The savings associated with each trip can be estimated as the unit savings per ton P times the mass of P transported between two cells. The system wide savings from manure distribution can then be estimated as the sum of the savings for all possible trips:

$$Savings_{redistribution} = \sum_{i=1}^{n}\sum_{j=1}^{q} c_{ij}x_{ij} \tag{3}$$

where c_{ij} is the savings when transporting manure from cell i to cell j [$/ton P], x_{ij} is the mass of the phosphorus transported from cell i to cell j [ton P], n is the total number of excess P cells, and q is the total number of deficit P cells.

3.2.2 Biogas Plant Savings

The savings associated with the construction of biogas plants can be estimated as the difference between the cost of transporting manure to biogas plants and the cost of building and operating the biogas plants and the value of the electricity produced by the biogas plants. The transportation savings were calculated using the same methods as in Section 3.2.1. There are no savings from reductions in fertilizer use, so the only components of the unit savings were the costs from the transportation. The equation for this was:

$$c_{ik} = -\frac{C_f + C_v * d_{ik}}{P_{M,i}} \tag{4}$$

where c_{ik} is the unit savings when transporting manure from cell i to cell j [$/ton P], C_f is the fixed cost of transporting manure [$/ton manure], C_v is the variable cost of transporting the manure [$/ton manure/km], $P_{M,i}$ is the phosphorus mass fraction in the manure at cell i [ton P/ton manure], $N_{M,i}$ is the nitrogen mass fraction in the manure at cell i [ton N/ton manure], and d_{ik} is the distance between cells i and j [km].

The fixed and variable costs of building and operating the biogas plants were estimated based on cost estimates from INC International (2013) after adjusting them to 2012 USD. All the costs associated with the biogas plant were annualized assuming a 20 year lifespan for each biogas plant. There were no fixed savings and the variable savings was the value of the electricity, which was taken from US Energy Administration (2012). The electricity value used was the mean price of electricity in the United States for the year 2012.

I start with the assumption that biogas plants are constructed on all grid cells that have excess P, which leads to k cells having biogas plants. The system savings was then found with the equation:

$$Savings_{biogas} = \sum_{i=1}^{n}\sum_{k=1}^{u} c_{ik} z_{ij} + \sum_{k=1}^{u} y_k \left[-c_0 + (l_1 * r * b * \eta - c_1) \sum_{i=1}^{n} \left(M_{P,i} z_{ik} \right) \right] \tag{5}$$

where c_{ik} is the unit savings when transporting manure from cell i to biogas plant k [$/ton P], z_{ik} is the mass of the phosphorus transported from cell i to cell j [ton P], c_0 is the fixed costs from building and operating biogas plants [$], c_1 is the variable costs from building and operating biogas plants [$/Btu], l_1 is the variable benefits from building and operating biogas plants, r is the energy produced per volume of biogas produced [Btu/m^3 methane], b is the volume of biogas produced per mass of manure used [m^3 methane/ton manure], η is the efficiency of energy generation [-], y_k is a binary variable that is 1 if a biogas plant is built at location k and 0 otherwise, and $M_{P,i}$ is the manure to phosphorus ratio in cell i [ton M/ton P].

3.3 Problem Formulation for Manure Distribution to Meet Crop Requirements

The second objective was to examine the costs and benefits of transporting manure from its origin to different locations. This involved simulating the transport of manure from excess cells (P Balance > 0) to deficit cells (P Balance < 0) in order to reduce the total excess phosphorus in the system. Two methods were used for this analysis, one simple heuristic algorithm and one linear optimization model. Cost was calculated for both methods, but was only a minimization objective for the linear optimization model.

Formulation of both methods required a set of key assumptions listed in Section 3.3.1. Following these assumptions, the simple heuristic algorithm is shown in Section 3.3.2 and the formal mathematical optimization is formulated in Section 3.3.3. Finally, Section 3.3.4 describes in detail the sources and methods used to determine the inputs (coefficients and constants) in the optimization model.

3.3.1 Transportation Assumptions

Multiple assumptions were made during the development of both methods. These assumptions are:

1. Application of manures beyond the crop nutrient requirements in any cell is undesirable.
2. Livestock and crop operations are separated and manure from any location can be applied to fields in any other location.
3. When applying manure to cropland, phosphorus requirements will be met before nitrogen requirements.
4. The cost of transporting manure is the only important cost in using manure as fertilizer.
5. The travel distance between any two cells is the linear distance between the center of the cells.
6. Sufficient infrastructure for manure storage already exists and additional storage would not be needed.

3.3.2 Simple Heuristic Algorithm for Manure Redistribution (No Biogas Plants)

I first developed a simple heuristic algorithm to simulate the distribution of manure between grid cells. This model was performed using the steps shown:

1. An excess cell i with a P balance > 0 was selected at random to be the manure origin cell.
2. The deficit cell j nearest to the excess cell with a P balance < 0 was selected to be the manure destination cell. If multiple cells were equidistant from the origin cell, the destination cell was selected at random from the closest cells.

3. Manure was transported from the origin cell to the destination cell and the P balance in each cell was updated to reflect the transport. The amount of manure transported was equal to the smaller of the excess at the origin cell and the deficit at the destination cell.
4. x_{ij} for the selected excess cell *i* and the deficit cell *j* was updated with the mass of phosphorus moved in Step 3.
5. Steps 1 - 4 were repeated until there were no remaining cells with excess manure.
6. The system savings associated with the run is then calculated using Equation 3.

The above heuristic algorithm was constructed to very roughly represent the behaviors that would arise from farmers attempting to redistribute manure in an uncoordinated manner when all excess phosphorus is required to be transported.

3.3.3 Simple Heuristic Algorithm for Manure Redistribution with Distance Constraints (No Biogas Plants)

Another second heuristic was made to represent behaviors that would arise when using manure as fertilizer is desirable, but no location is willing to lose money transporting manure. This heuristic was performed using the steps shown:

1. An excess cell *i* with a P balance > 0 was selected at random to be the manure origin cell.
2. A maximum transport distance was calculated for the manure in cell *i* by setting c_{ij} in Equation 2 to 0 and solving for d. This result represented the maximum distance that manure could be transported from cell *i* without losing money.
3. The deficit cell *j* nearest to the excess cell with a P balance < 0 was selected to be the manure destination cell. If multiple cells were equidistant from the origin cell, the destination cell was selected at random from the closest cells.
4. The distance between the origin cell *i* and deficit cell *j* was calculated and compared to d from Step 2. If *d* was smaller than the distance between the two cells, origin cell *i* was removed from the algorithm and it started again from Step 1. If *d* was larger than the distance between the two cells, the algorithm continued to Step 5.

5. Manure was transported from the origin cell to the destination cell and the P balance in each cell was updated to reflect the transport. The amount of manure transported was equal to the smaller of the excess at the origin cell and the deficit at the destination cell.
6. x_{ij} for the selected excess cell *i* and the deficit cell *j* was updated with the mass of phosphorus moved in Step 5.
7. Steps 1 - 6 were repeated until there were no remaining cells with excess manure (except those that are too far from the closest deficit cell).
8. The system savings associated with the run is then calculated using Equation 3.

Unlike the algorithm in Section 3.3.2, this algorithm stopped manure transportation in cases where the cost of transportation exceeded the savings from fertilizer. This contrasts with the coordinated approach that follows from structuring the problem as an optimization problem as in the later sections.

3.3.4 Linear Optimization Model Formulation for Manure Redistribution (Optimization Formulation 1)

I then formulated a linear optimization model that would maximize the savings (Equation 3) associated with manure redistribution from fixed excess P to fixed deficit P locations. Optimization Formulation 1 was solved using IBM ILOG CPLEX Optimization Studio Version 12.8 using the dual simplex optimizer. The five constraints used in this optimization formulation are described below.

$$max \sum_{i=1}^{n} \sum_{j=1}^{q} c_{ij} x_{ij}$$

s.t.

$$\sum_{j=1}^{q} x_{ij} \le S_i;\ \forall\, i$$

$$\sum_{i=1}^{n} x_{ij} \le D_j;\ \forall\, j$$

Constraint 2

Constraint 3 $$\sum_{i=1}^{n}\sum_{j=1}^{q} x_{ij} \geq f * \sum_{i=1}^{n} S_i$$

Constraint 4 $$e_{ij}x_{ij} \geq 0;\ \forall\ i,j$$

$$x_{ij} \geq 0;\ \forall\ i,j$$

Parameters:

n = number of P excess locations (supply points)

q = number of P deficit locations (demand points)

c_{ij} = savings from moving manure from cell i to cell j [$/ton P]

S_i = net phosphorus supply at cell i [ton P]

D_i = net phosphorus demand at cell j [ton P]

f = minimum fraction of total excess manure to be transported [-]

e_{ij} = constant defining if transportation is possible between cell *i* and cell *j* [-]

Variables:

x_{ij} = amount of phosphorus transported from cell i to cell j [ton P]

Constraints 1 and 2 relate to the mass of P that can be transported between two cells. Constraint 1 restricts the amount of phosphorus that can leave an excess cell *i* to the amount of excess P present in the cell Si, while Constraint 2 restricts the amount of phosphorus that can enter a grid cell to the mass of P demand in that cell Dj. Constraint 3 provides a lower bound on the minimum fraction of the total excess P in the excess cells that must be moved. When f is set to 0, the optimization model will find the solution that maximizes savings without regard to the amount of phosphorus remaining in excess cells. Increasing f then allows for different solutions to be found to explore the relationship between the amount of manure transported and the total savings from transportation. Constraint 4 is a constraint on the distance that manure can be transported based on the costs and benefits of transporting manure between two cells. This was added in order to prevent transporting manure excessively large distances and to ensure that each trip provided a sufficient benefit. The parameter e_{ij} was defined with the equation:

$$e_{ij} = \begin{cases} 1 \; if \; \left[\frac{C_{PF}}{P_F} + \frac{C_{NF}}{N_F} * \frac{N_{M,i}}{P_{M,i}} - T * \frac{C_f + C_v * d_{ij}}{P_{M,i}}\right] \geq 0 \\ -1 \qquad\qquad Otherwise \end{cases} ; \forall \; i, j \tag{6}$$

where e_{ij} is a constant set to 1 when the benefit:cost ratio is high enough to move manure from cell i to cell j [-] and set to -1 when it is not, C_{PF} is the cost of superphosphate fertilizer [$/ton fertilizer], C_{NF} is the cost of ammonium nitrate fertilizer [$/ton fertilizer], C_f is the fixed cost of transporting manure [$/ton manure], C_v is the variable cost of transporting the manure [$/ton manure/km], P_F is the phosphorus mass fraction in superphosphate [ton P/ton fertilizer], N_F is the nitrogen mass fraction in ammonium nitrate fertilizer [ton N/ton fertilizer], $P_{M,i}$ is the phosphorus mass fraction in the manure at cell i [ton P/ton manure], $N_{M,i}$ is the nitrogen mass fraction in the manure at cell i [ton N/ton manure], d_{ij} is the distance between cells i and j [km], and T is the minimum benefit:cost ratio for transportation between two locations [-].

With this parameter, Constraint 4 was used to prevent transport between two cells when the ratio of the benefits to the costs is below T. For example, when T is set to 1, this constraint prevents transport between two cells in any case where the cost of transporting the manure is greater than the benefits the manure would provide. However, if T was set to 2, this constraint would prevent transport between two cells in any case where the benefits from the manure are less than twice the cost of the manure transportation. Typically, T = 1 would be the ideal equilibrium. Trips where T approaches 0 may occur in cases where transport is required or other factors are prioritized above the cost, while trips above 1 may not occur when there are additional factors causing transport to be less desirable.

The distance that Constraint 4 restricts transport to is dependent on the N and P content of the manure. Manure with higher nutrient content is able to be transported further since it replaces a greater amount of fertilizer for each ton of manure transported. Figure 1 shows the transport distances of different livestock if the manure being transported is purely from the livestock shown. In the model, this distance will vary between cells as livestock types vary regionally. As For example, the maximum transport distance for livestock manure varies from a low of 0 km for milk cows to a high of 990 km for broiler chickens.

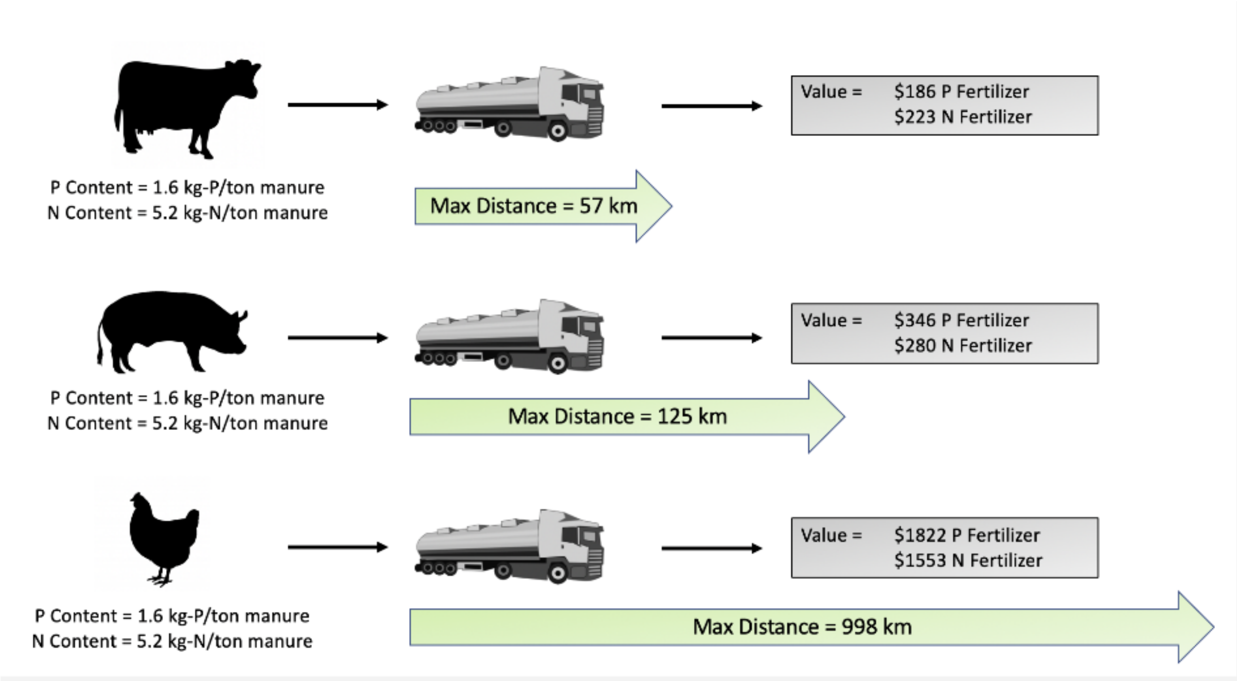

Figure 1. Nutrient content and transport distance for beef cows, hogs, and broiler chicken.

3.4 Problem Formulation for Manure Distribution to Meet Crop Requirements and Raw Material for Biogas Plants

The third objective was to examine the costs and benefits of constructing and operating biogas plants that use the excess manure as fuel. This involved using linear optimization models to determine the best locations to build and operate biogas plants when taking into account the costs of building and operating biogas plants and the cost of transporting the manure from its source to the biogas plants. Two linear optimization models were used in this analysis, one where balancing crop requirements was done before biogas plant usage was considered and one where balancing crop requirements and biogas plant usage were considered simultaneously.

Formulation of both methods required a set of key assumptions listed in Section 3.4.1. Following these assumptions, the formal mathematical optimization for the first model is formulated in Section 3.4.2. Finally, the formal mathematical optimization for the first model is formulated in Section 3.4.3.

3.4.1 Assumptions about Biogas Operation

Multiple assumptions were made during the development of both models. These assumptions are:

1. The important costs are the cost of constructing and operating the biogas plants and the cost of transporting manure to the biogas plants.
2. Application of nutrients beyond the requirements in any cell is undesirable.

The distance between any two cells is the distance between the center of the cells when travelling in a straight line.

3.4.2 Sequential Linear Model Formulation (Optimization Formulation 2)

The first optimization formulation for building and operating biogas was developed under the assumption that transporting manure for use as fertilizer would be the preferred option when possible, based on the results of Optimization Formulation 1. The goal of this optimization formulation was to determine the location of biogas plants to be built and the transportation of the manure to biogas plants in order to minimize the costs of the biogas plants.

The objective function of Optimization Formulation 2 maximizes the system savings from building and operating biogas plants as defined in Section 3.2.2 (equation numbers). The variable y_k is set to be equal to 1 if there is a biogas plant at that grid cell, and 0 otherwise. Constraints 1 and 2 are used to describe the limits on P transport from a grid cell to the biogas plant. This is formulated similar to the Optimization Formulation 1, where constraint 1 restricts the amount of phosphorus that can leave excess cell i to the amount of excess manure present in the cell, and Constraint 2 provides a lower bound on the minimum fraction of the total excess P in the excess cells that must be moved. Finally, Constraint 3 is used to both limit the size of biogas plants and prevent manure from being transported to locations where biogas plants are not being built. The maximum size of the biogas plant is defined as b, and Constraint 4 ensures that the manure transported to the cell k is less than b, when $y_k = 1$. However, when $y_k = 0$, the amount of manure that can be transported to the cell will be set to 0 since the cell does not have a biogas plant to process the manure. The optimization problem was formulated as follows:

$$max \sum_{i=1}^{n} \sum_{k=1}^{m} c_{ik} z_{ik} + \sum_{k=1}^{m} \left[-c_0 y_k + (l_1 * r * b * \eta - c_1) \sum_{i=1}^{n} \left(M_{P,i} z_{ik} \right) \right]$$

s.t.

Constraint 1 $$\sum_{k=1}^{m} z_{ik} \leq S_i;\ \forall\, i$$

Constraint 2 $$\sum_{i=1}^{n} \sum_{k=1}^{m} z_{ij} \geq f * \sum_{i=1}^{n} S_i$$

Constraint 3 $$\sum_{i=1}^{n} \left(M_{P,i} z_{ik} \right) \leq b y_k;\ \forall\, k$$

$$z_{ik} \geq 0;\ \forall\, i, k$$

$$y_k = 0{,}1;\ \forall\, k$$

Parameters:

i = Index of net P supply locations

k = Index of potential biogas locations

n = Number of P excess locations

m = Number of potential biogas locations

c_{ik} = Savings from moving manure from cell i to biogas plant j [$/ton P]

c_0 = Fixed costs from building and operating a biogas plant [$]

c_1 = Variable costs from building and operating a biogas plant [$/kWh]

l_1 = Variable benefits from building and operating a biogas plant [$/Btu]

r = Energy produced per volume of gas produced [Btu/m3 methane]

b = Volume of gas produced per mas of manure used [m3 methane/ton manure]

η = Efficiency of electrical energy generation [-]

$M_{P,i}$ = Manure to phosphorus ratio in cell i [ton M/tonP]

S_i = total phosphorus supply at cell i [ton P]

f = minimum fraction of excess manure to be transported [-]

b = Maximum manure capacity of a biogas plant [tons M]

Variables:

z_{ik} = amount of phosphorus transported from cell i to cell j [ton P]

y_k = Is 1 of a biogas plant is built at location j, 0 otherwise

3.4.3 Simultaneous Linear Model Formulation (Optimization Formulation 3)

The second optimization formulation for building and operating biogas was built under the assumption that transporting manure for use as fertilizer would occur at the same time as transporting manure for use in biogas plants. This optimization model maximizes the systemwide profits without regard for the method of using manure. The goal of this optimization formulation is to determine the location of biogas plants to be built, the mass of the manure transported to biogas plants, and the mass of the manure transported to excess cells in order to minimize the system costs.

Mass restrictions were used as a constraint in order to ensure that any manure transported is available and is transported to a location where it is needed. Constraint 1 restricts the amount of phosphorus that can leave excess cell *i* to the amount of excess manure present in the cell. Likewise, Constraint 2 restricts the amount of phosphorus that can enter a deficit cell to the size of the deficit in the cell. Constraint 3 provides a lower bound on the minimum fraction of the total excess P in the excess cells that must be moved. This can be used to find the trade-offs between the total savings and total remaining excess P by varying *f* when solving Optimization Formulation 3. Constraint 4 was used to control the size of the biogas plants and prevent manure from being transported to locations where biogas plants were not built. In cells where $y_j = 1$, the maximum amount of manure transported to it would be set to the defined maximum. However, when $y_j = 0$, this amount of manure able to be transported to the cell would be set to 0. The optimization problem is formulated as follows:

$$max \sum_{i=1}^{n}\sum_{j=1}^{q} c_{ij}x_{ij} + \sum_{i=1}^{n}\sum_{k=1}^{n} c_{ik}z_{ik} + \sum_{k=1}^{n}\left[-c_0y_k + (l_1 * r * b * \eta - c_1)\sum_{i=1}^{n}\left(M_{P,i}z_{ik}\right)\right]$$

s.t.

Constraint 1 $$\sum_{j=1}^{q} x_{ij} + \sum_{k=1}^{n} z_{ik} \leq S_i;\ \forall\, i$$

Constraint 2 $$\sum_{i=1}^{n} x_{ij} \leq D_j;\ \forall\, j$$

Constraint 3 $$\sum_{i=1}^{n}\sum_{j=1}^{q} x_{ij} + \sum_{i=1}^{n}\sum_{k=1}^{n} z_{ik} \geq f * \sum_{i=1}^{n} S_i$$

Constraint 4 $$\sum_{i=1}^{n}\left(M_{P,i}z_{ik}\right) \leq by_k;\ \forall\, k$$

$$x_{ij} \geq 0;\ \forall\, i,j$$

$$z_{ik} \geq 0;\ \forall\, i,k$$

$$y_k = 0{,}1;\ \forall\, k$$

Parameters:

n = number of P excess locations

k = number of potential biogas locations

c_{ij} = savings from moving manure from cell i to cell j [$/ton P]

c_{ik} = savings from moving manure from cell i to biogas plant j [$/ton P]

c_0 = Fixed savings from building and operating a biogas plant [$]

c_1 = Variable savings from building and operating a biogas plant [$/kWh]

l_1 = Variable benefits from building and operating a biogas plant [$/kWh]

r = Energy produced per volume of gas produced [Btu/m3 methane]

b = Volume of gas produced per mas of manure used [m3 methane/ton manure]

η = Efficiency of electrical energy generation [-]

$M_{P,i}$ = Manure to phosphorus ratio in cell i [ton M/tonP]

S_i = total phosphorus supply at cell i [ton P]

D_i = total phosphorus demand at cell j [ton P]

f = minimum fraction of excess manure to be transported [-]

b = Maximum manure capacity of a biogas plant [tons M]

Variables:

x_{ij} = amount of phosphorus transported from cell i to cell j [ton P]

z_{ij} = amount of phosphorus transported from cell i to cell j [ton P]

y_j = Is 1 of a biogas plant is built at location j, 0 otherwise

The objective function of Optimization Formulation 4 minimizes the system cost of transporting the manure and building and operating biogas plants. The objective function was formed by summing the system savings functions for both manure redistribution and biogas operation from Sections 3.2.1 and 3.2.2.

Chapter 4 – Results and Discussion

This chapter first describes in detail a grid-scale P balance covering CONUS in Section 4.1. Four different transportation scenarios are then explored in order to examine the costs and benefits of transporting manure in Section 4.2. Section 4.3 explores the costs and benefits of biogas plant construction for utilizing excess manure. Finally, Section 4.4 summarizes the key findings of this study.

4.1 Grid Scale P Balance

Based on the methods described in Section 3.1, in 2012, there was a total of 2,040,000 tons of crop P uptake and 980,000 tons of manure P production across the 3,142 counties in the United States. When split across the 78,000 grid cells (6 km by 6 km), 450,000 tons of the manure P was used to satisfy crop requirements within the same cell, satisfying 22% of the phosphorus needs of crops grown in the US. This also leaves 530,000 tons of manure P in locations where it is not needed for crop fertilizer. Figure 4 shows the location of the manure P excess and the crop P requirements.
All four of the regions in Figure 2 have greater crop P requirements than manure P production. However, this is only mostly true when looking at the sub-regions. Both the New England and South Atlantic districts produce more manure P than the crop requirements within those regions.

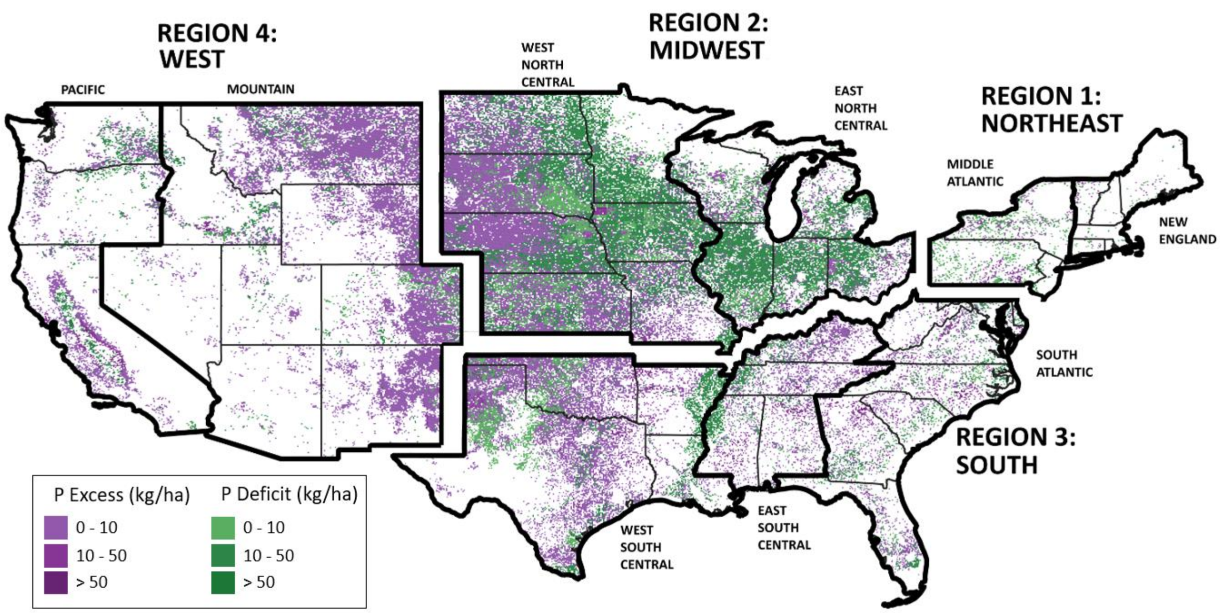

Figure 2. Map of P Excess and P Deficits in the contiguous United States ignoring inorganic fertilizer application. Excess/deficits computed for 6 km by 6 km grid cells for 2012.This shows the spatial disconnect between areas that are predominantly used for agriculture (purple) and areas where crops dominate (green). White space on the map indicates non-agricultural land based on the land use raster ((“USDA National Agricultural Statistics Service Cropland Data Layer,” 2012))

There is a significant spatial disconnect between the crop P demand and the manure P production. While all four regions have areas where the crop P demand is greater than the manure P production, there are significantly more locations where this occurs in the Midwest than in any of the other regions. This can be seen in Figure 3 in the P Excess histogram for Region 2. Conversely, Region 4, the West, has fewer locations where the crop P demand is higher than the manure P production. Region 4 also has a larger fraction of locations where the manure P production is in excess by between 0 and 10 kg/ha. Region 1 is unique in that the crop P production and the manure P demand are similar, although they are still spatially disconnected.

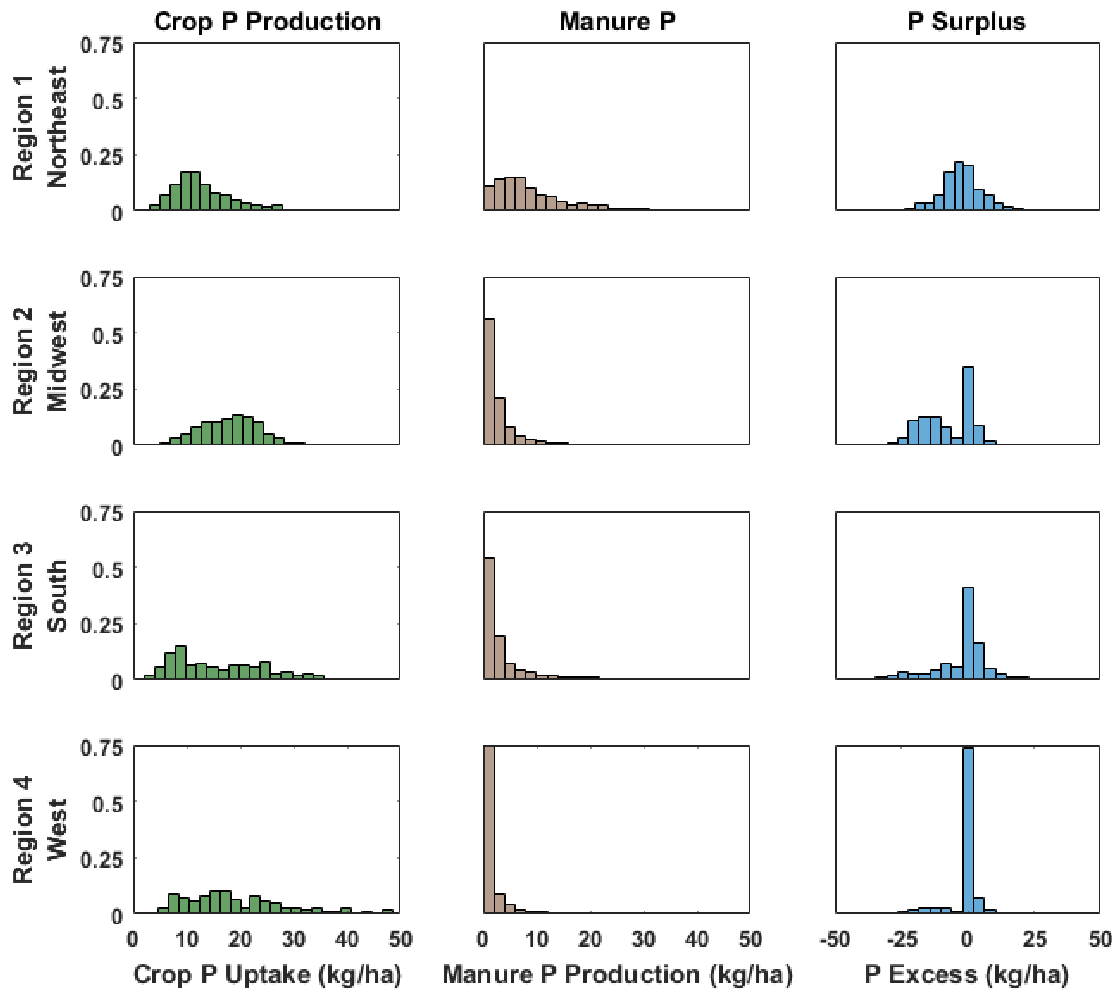

Figure 3. Histogram of Crop P Uptake, Manure P Production, and P Excess for the grid cells in each census region of the contiguous United States. Grid cells that have no P in a category are omitted from that category (i.e, a cell with 0 crop P requirement and some manure P would appear in the Manure P and P Surplus histograms but not the Crop P Production histogram)

In addition to regional differences in crop P demand and manure P production, there are also significant regional differences in the N and P content of the manure in each region, listed in Table 5. The N and P content in manure varies between different livestock, resulting in different mean N and P content in different regions depending on the dominant livestock in the region. The most notable difference is the significantly higher N and P content in the manure of chicken, resulting in significantly higher mean N and P content in the regions where chicken are more prevalent. This effect can be seen in the South region, where the mean N and P content are each more than double that of the next highest region.

Table 5. Manure P production of cattle, hogs, and chicken and the mean N and P content of manure in each region.

Region	P from Cattle (tons)	P from Hogs (tons)	P from Chicken (tons)	Total Excess P (tons)	Mean P Content in Manure (kg P/ton)	Mean N Content in Manure (kg N/ton)
USA	**599,855**	**155,061**	**227,734**	**982,651**	**2.6**	**6.6**
Northeast	**46,085**	**2,999**	**9,440**	**58,523**	**1.8**	**4.5**
New England	6,972	70	699	7,742	1.3	3.4
Middle Atlantic	39,113	2,929	8,740	50,782	1.9	4.6
Midwest	**247,158**	**114,171**	**36,654**	**397,984**	**1.9**	**4.9**
East North Central	83,401	26,358	16,365	126,124	1.9	4.4
West North Central	163,757	87,814	20,289	271,859	1.9	5.1
South	**138,505**	**35,047**	**172,014**	**345,566**	**4.2**	**10.2**
South Atlantic	24,906	25,460	79,133	129,499	5.1	11.9
East South Central	25,969	1,933	47,191	75,093	4.8	11.6
West South Central	87,630	7,654	45,689	140,973	1.2	3.8
West	**168,107**	**2,844**	**9,628**	**180,578**	**1.3**	**3.9**
Mountain	84,803	2,527	1,444	88,774	1.2	3.8
Pacific	83,304	316	8,184	91,804	1.4	4.0

4.2 Ability of Surplus N and p to Meet Countrywide Crop Requirements

Section 4.1 established that the amount of manure P was able to meet 22% of the United States crop P requirements without leaving the grid cell it was produced in. However, there is enough excess manure P remaining in cells to meet an additional 26% of the total United States crop P requirements (assuming unlimited transport). This section examines scenarios where manure is transported from the source grid cell to other grid cells with a P deficit.

Five different transportation scenarios were explored in order to examine the costs and benefits of transporting manure. The first scenario uses the simple heuristic manure redistribution algorithm from Section 3.2 to explore the costs of transportation when there are no top-down controls on where the manure is moved. Scenario 1 requires manure to be moved such that all manure P excess is utilized to satisfy P deficits and there are no limits on the distance transported. The second scenario uses a similar heuristic algorithm to Scenario 1 but adds a constraint on how far manure can travel based on the cost of transportation and the benefits from spreading the manure. The third, fourth, and fifth scenarios use Optimization Formulation 1 to examine the trade-offs between the cost of transportation and the amount of fertilizer transported. This is done as an example of manure transportation when there are top-down controls on where manure is moved to. Scenario 3 examines the effect of transportation with distance restrictions on a national level. Scenario 4 examines the effect of transportation with and without distance limits for a single state. Scenario 5 compares how the national scale results change when the historically lower price of fertilizer is used instead of 2012 fertilizer costs.

4.2.1 Scenario 1: Heuristic Redistribution of 100% of Manure P Excess, No Constraints

Results show that, assuming no constraints on the transport of manure, 48% of the country's P requirement and 18% of the country's N requirement for crops could be met by using livestock manure as a fertilizer source. Without consideration of any constraints on manure transport, I find that in the Northeast region in Figure 3, 37% of the crop P requirements and 100% of the crop P requirements could be met through the spreading of manure. The effect is particularly pronounced in the South region, where recycling of manure could result in an 82% reduction in commercial N and P fertilizer use. In the Midwest, however, the effects are less dramatic. In these areas, where livestock densities are lower and crop production is intensive, manure N and P can meet only 12 and 32% of N and P crop requirements, respectively, and only a 14% decrease in P fertilizer use would be possible.

Under this no-constraint scenario, the median transport distance for manure ranges from 6-121 km in the four regions, with the US-scale mean and median distances of 63 and 22 km, respectively. The regional results are listed in Table 6. As described in Section 2.2.1, the savings associated with this transport are calculated as the difference between the actual costs of transport (fuel and vehicle costs) and the costs saved on the purchase of commercial fertilizer. Accordingly, I find that savings per trip range from $-2,422 to $4,590 with mean and median savings of $730 and $750, respectively. Overall, full transport of all excess manure would have savings of $2.3 billion dollars.

While the savings across the system is substantial, this result also has significant local costs in some areas, as captured by the negative savings. At the national scale, local costs occurred in 8% of the trips taken using this redistribution approach because the costs were higher than the benefits. This effect was particularly pronounced in the New England region, where 61% of trips incurred losses. This was also more common in the Middle Atlantic, South Atlantic, and Pacific regions, where 15%, 15% and 16% of trips incurred losses, respectively. Conversely, local losses were uncommon in the East North Central and West North Central, where local losses occurred for 0% and 0.6% of trips, respectively. This is highly undesirable and lead me to look into solutions where no losses occurred on individual trips.

Table 6. Transport distances and associated costs, by region (Scenario 1, no caps on distances traveled).[2]

Region	Maximum Transport Distance (km)	Mean Transport Distance (km)	Median Transport Distance (km)	Mean Cost per Trip (USD)	Mean Fertilizer Cost Offset per Trip (USD)	Total Savings (million USD)
USA	**-**	**63**	**22**	**465**	**1,028**	**2,345**
Northeast	**-**	**88**	**42**	**628**	**828**	**35**
New England	-	173	171	1,013	768	-19
Middle Atlantic	-	66	34	527	844	54
Midwest	**-**	**18**	**8**	**255**	**1,054**	**981**
East North Central	-	14	6	235	903	257
West North Central	-	19	8	260	1,085	723
South	**-**	**113**	**66**	**739**	**1,599**	**1,110**
South Atlantic	-	194	121	1,086	2,124	229
East South Central	-	98	65	675	1,927	361
West South Central	-	88	57	630	1,311	521
West	**-**	**53**	**27**	**465**	**1,028**	**219**
Mountain	-	51	25	453	1,045	192
Pacific	-	65	32	522	942	27

4.2.2 Scenario 2: Heuristic Redistribution of 100% of Manure P Excess, with Constraints on Net Costs for Each Individual Trip

As described above, the first scenario showed that even though very high overall savings were achieved, local costs occurred frequently with a livestock manure redistribution strategy focused on eliminating all excess manure P. Although this goal ensures maximum benefits from a water quality perspective, these high costs would undoubtedly be prohibitive if borne by individual farmers. Also, environmental gains from transport across the longest distances would likely be

[2] Refer to Equations 2 and 3

incremental and have other negative environmental externalities, especially regarding greenhouse gas emissions associated with fossil fuel use associated with transport.

The second scenario used a similar algorithm (Section 3.3.3) to simulate the transport of manure for fertilizer while preventing any individual trips from losing money. Under these conditions, 57,000 tons less manure is transported compared to Scenario 1, meeting a total of 45% of the national crop P requirement. This reduction in P transport led to an increase in total savings, up to $2.8 billion USD. The effect of the transportation restrictions was most noticeable in the New England, South Atlantic, and Pacific subregions. New England went from a losing money to having some savings, while the savings for the South Atlantic and Pacific subregions increased by 69% and 560%, respectively. The East North Central and West North Central regions experienced few changes from Scenario 1 as nearly all the trips in these regions were originally short enough to provide savings.

Table 7. Transport distances and associated costs, by region (Scenario 2, constraints on distance travelled).

Region	Maximum Transport Distance (km)	Mean Transport Distance (km)	Median Transport Distance (km)	Mean Cost per Trip (USD)	Mean Fertilizer Cost Offset per Trip (USD)	Total Savings (million USD)
USA	**585**	**47**	**19**	**440**	**1,158**	**2,816**
Northeast	**278**	**39**	**27**	**421**	**837**	**79**
New England	278	52	33	473	849	7
Middle Atlantic	144	38	27	415	836	71
Midwest	**273**	**17**	**8**	**251**	**965**	**346**
East North Central	85	14	6	237	801	258
West North Central	273	18	8	258	1,046	726
South	**585**	**89**	**51**	**663**	**1,675**	**865**
South Atlantic	585	146	83	843	1,994	388
East South Central	510	88	54	635	1,905	366
West South Central	328	69	46	586	1,419	565
West	**225**	**37**	**24**	**415**	**828**	**436**
Mountain	225	38	24	389	884	255
Pacific	194	35	25	440	774	179

4.2.3 Scenario 3: Optimal Manure Redistribution with Constraints on Net Costs for Each Individual Trip (Optimization Formulation 1)

Scenario 3 uses Optimization Formulation 1 to maximize savings from transporting manure. The redistribution heuristic algorithm from Scenarios 1 and 2 is not designed to distribute manure in a way that maximizes overall savings. This scenario will examine how to redistribute manure when maximizing savings is the priority.

In the third redistribution scenario, I assume that transport distances are limited based on net costs associated with transport. The constraint on net transportation costs is specified such that a manure transfer between any two cells is only feasible (e.g., allowed) if it yields a non-negative net cost (local net cost constraint). This was done using T = 1 in Equation 6 in Section 2.2.3. I also assumed no constraint on the amount of excess P remaining in cells (f = 0).

Solving Optimization Formulation 1 with the constant *f* set to 0 resulted in the solution with the maximum savings. This solution has an overall savings of $3,013 million dollars at the national scale, exceeding the solution from Scenario 1 by $670 million. This scenario also removes the possibility of monetary losses occurring on individual trips, unlike Scenario 1. However, maximizing the savings from manure transportation results in less manure being transported. All excess P was transported in Solution 1, while 57 thousand tons of excess P is left behind in Solution 3. This solution reduced the amount of excess P transported by the same amount as in Scenario 2 but increased the total savings by nearly $200 million USD.

Just as in the no-constraint scenario, the mean and median transport distances varied by region, For example, in the Northeast region, the mean trip distance (36 ± 38 km) is longer than that in the Midwest region, which encompasses much of the U.S. corn belt (15 ± 21 km). However, a closer look at these transport distances shows that the distribution of distances in the Northeast region is bimodal (or has a long tail), with one peak at 10 km, and then a large number of trips at distances greater than 70 km. This distribution is indicative of relatively small percent cropped area across the region. Despite the high spatial proximity between crop and livestock production in this area, the land required for zero-P surplus spreading of manure is far less than needed, thus leading to longer transport distances. Conversely, in the Midwest ecoregion, which encompasses much of the U.S. corn belt, livestock production is more concentrated, but available land for spreading is ample, leading to shorter transport distances (<15 km). Another notable ecoregion is the South Atlantic subregion. Manure in this region has a significantly higher N and P fraction than in other region due to the livestock dominant in the region. This, along with lower crop production in the region, resulted in mean transport distances of 66 ± 89 km. As the densities of different livestock types also vary regionally across the U.S., the maximum transport distance, under the no local cost constraint, also varied regionally (Table 8). The longest distances could be traveled in the Region 3 of the U.S., whereas distances were significantly more limited in all other regions.

Table 8. Transport distances and associated costs, with cost-based cap on distances traveled, by region.

Region	Maximum Transport Distance (km)	Mean Transport Distance (km)	Mean Cost per Trip (USD)	Mean Fertilizer Cost Offset per Trip (USD)	Total Savings (million USD)	Total Excess P Transported (thousand tons)
USA	**696**	**38**	**386**	**1,158**	**3,013**	**530**
Northeast	**279**	**36**	**389**	**835**	**83**	**18**
New England	279	42	395	876	7	2
Middle Atlantic	278	36	389	831	75	17
Midwest	**255**	**15**	**231**	**960**	**1,004**	**153**
East North Central	78	13	226	797	262	43
West North Central	255	15	234	1,042	742	110
South	**696**	**66**	**560**	**1,668**	**1,452**	**264**
South Atlantic	696	105	715	1,997	430	84
East South Central	427	64	513	1,893	398	66
West South Central	336	53	503	1,413	625	114
West	**252**	**33**	**370**	**830**	**473**	**95**
Mountain	233	33	348	886	271	49
Pacific	252	33	390	776	203	46

The remaining P after transportation is shown in Figure 3. The remaining excess P is located in areas with large amounts of livestock and little nearby cropland. Although there are locations with excess P across the country, the largest remaining excess P locations are in New Mexico, Texas, North Carolina, and Tennessee.

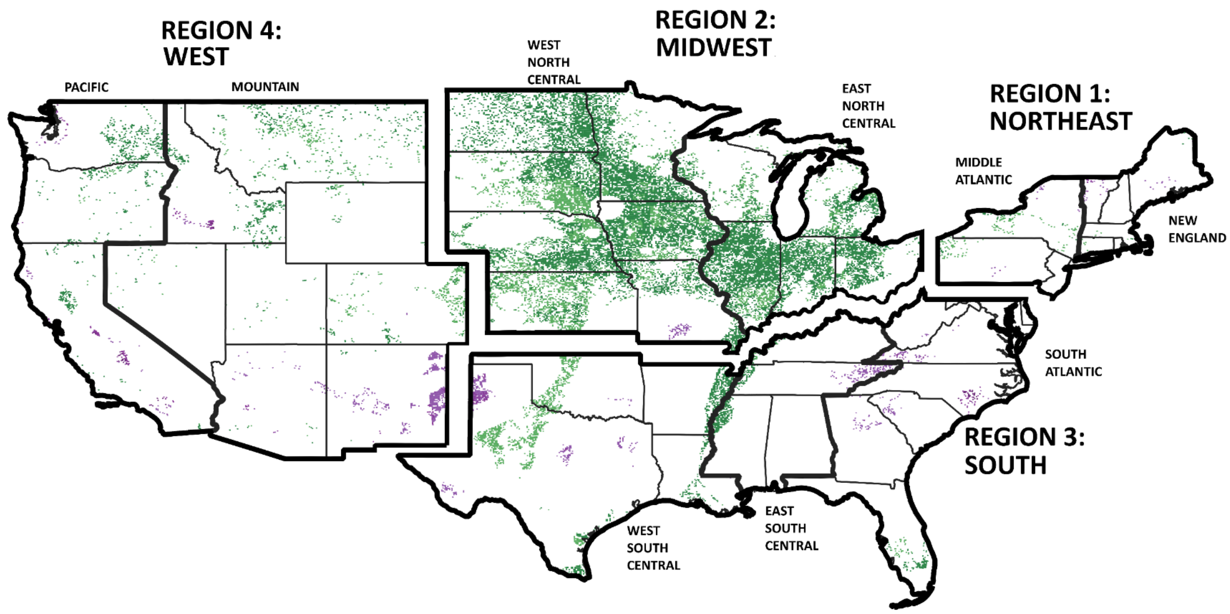

Figure 4. Map of P Excess and P Deficits in the contiguous United States after distance limited manure transportation.

4.2.4 Tradeoffs associated with Excess P remaining and National Scale Savings for Various Manure Redistribution Scenarios

The above solution found for transporting manure with distance restrictions was done with the goal of maximizing savings, without any consideration for Excess P remaining on the land, and thus water quality impacts (Point A in figure below). In order to examine how increasing the amount of manure P transported affected the solution, the constraint f in the Optimization Formulation was increased until Constraints 3 and 4 were both binding constraints. When solving Optimization Formulation 1 under these conditions, savings were maximized while ensuring that the maximum amount of manure that was possible to move under the limited distance constraint was moved.

This resulted in a solution where the overall savings was reduced by $100 million dollars in exchange for an increase in manure P transportation of 35 thousand tons (Point B in figure below). The difference between these two solutions is shown in Figure 5. Compared to the no constraint solutions, both distance limited solutions provided greater system savings and less total P transport, as well as ensuring that there were no losses from individual trips.

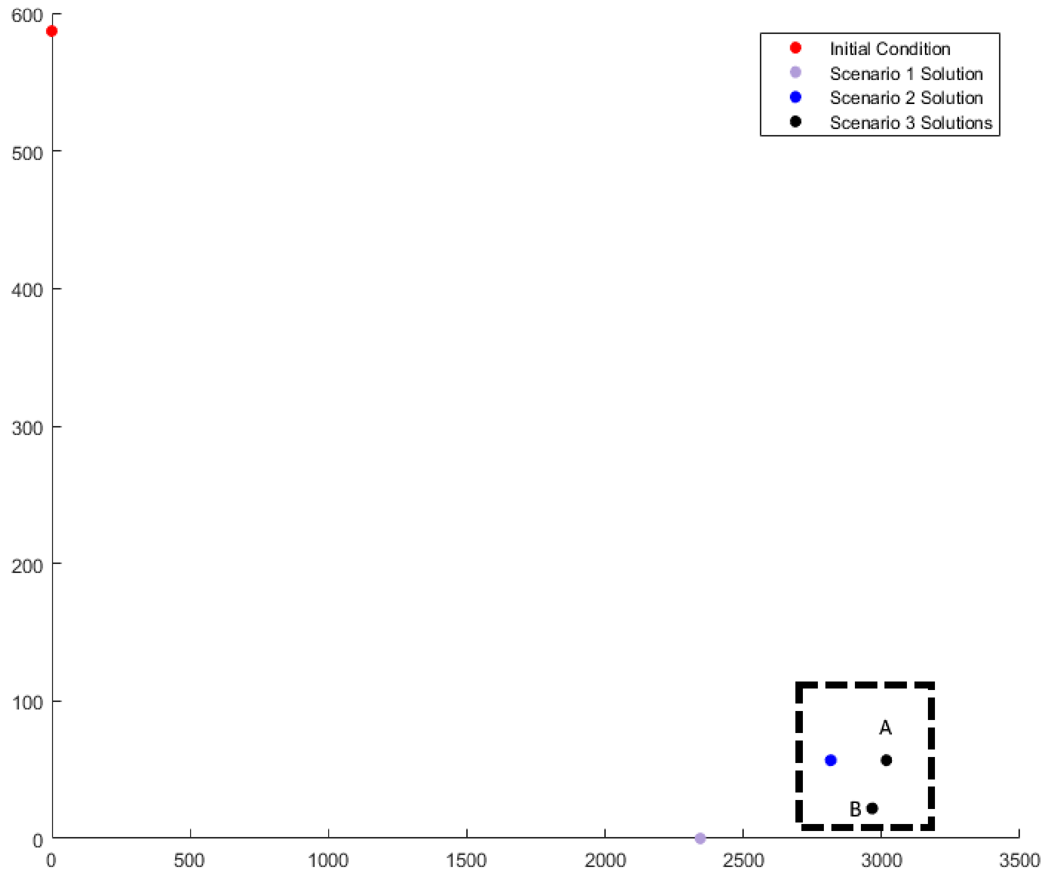

Figure 5. Savings and reduction of excess phosphorus associated with manure redistribution. The initial condition shows the mass of excess phosphorus across CONUS before any changes are made. The Scenario 1 solution represents the solution described in Section 4.2.1. The Scenario 2 solution represents the solution described in Section 4.2.2. Scenario 3 solution A represents the solution to Optimization Formulation 1 when maximizing exclusively for savings. Scenario 3 solution B represents the solution to Optimization Formulation 1 when Constraints 3 and 4 are both binding and the maximum manure P is being transported.

The difference in both savings and manure P transported between points A and B in Figure 4 demonstrated that there is a tradeoff between the two objectives when optimizing. The tradeoff curve was built by varying variable f in Formulation 1 within the values from points A and B (0 and 0.96, respectively) and then resolving the optimization model. This produced solutions located between the two extreme solutions and these new solutions create the tradeoff curve shown in Figure 6.

Following the completion of the tradeoff curve with a zero cost constraint, trade-off curves under more conservative conditions were built. The constant T in Constraint 4 of Optimization Formulation 1 was changed from 1 to 1.33 and 2 in order to further restrict the distance limitation from the original solution. This changed the zero-cost limitation from the previous section to a constraint where the fertilizer benefits had to be 33% and then 100% greater than the cost of transportation. The tradeoff curve for T = 1.33 was then built by varying f in Formulation 1 between the values of 0 and 0.9. There is no tradeoff curve for T = 2 because Constraint 3 in Formulation 1 was nonbinding and varying it did not impact the solution. The tradeoff curve and point resulting from these solutions are shown in Figure 6.

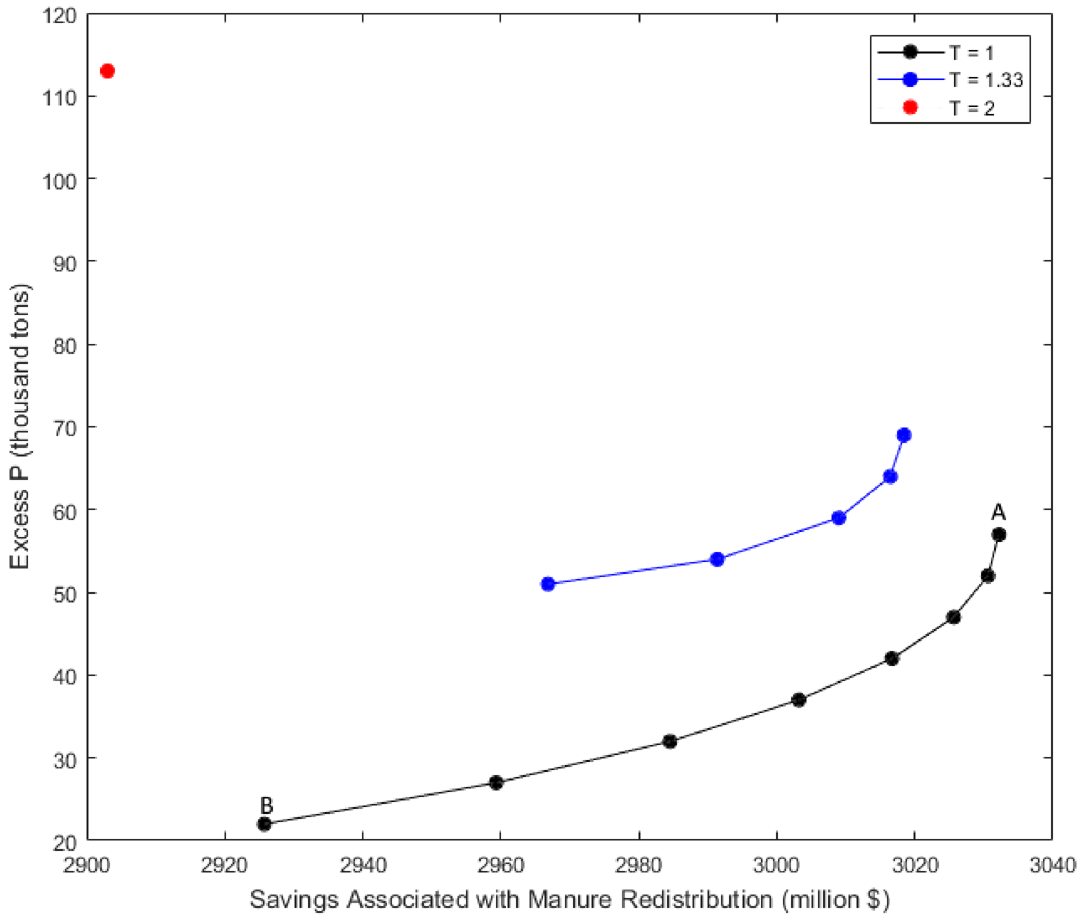

Figure 6. Trade-off curve between cost savings and remaining excess P within CONUS with varying cost restrictions. Point A represents the result with the maximum savings and Point B represents the result with the minimum remaining excess P. As T increases, the systems savings possible decrease and the remaining excess P increases.

The first curve builds on the solutions from Section 4.2.2 and is for when T = 1. On the leftmost edge of this curve, marked point A, is the point with the least amount of excess P remaining. This point has only 22,000 tons of excess P remaining across the country and represents the best possible solution to Optimization Formulation 1 when minimizing excess P is the priority. As the curve moves to the right, the savings from transportation increase, but the amount of excess P remaining also increases. This occurs because leaving more P in excess cells allows for shorter trips in many locations, increasing the savings from those trips. At the far right of that curve is the point of optimal savings, with a total savings of 3,032 million dollars and a total of 66,000 tons of P remaining in excess cells.

The second curve in Figure 6 is for when T = 1.33. The increase in the minimum benefit:cost ratio for local trips reduced the number of possible local trips. This decrease resulted in less P transport and less system savings but increased the minimum local savings. Like the first curve, it starts with the optimal excess P reduction on the left side of the curve and eventually reaches the optimal savings for the curve on the right side.

The third element of Figure 6 is the point for when T = 2. Like the second curve, the increase in f resulted in a reduction of potential local trips, reducing both the P transported and the system savings. Unlike the first two elements of the graph, this result is a single point. This is because that point represents the optimal solutions for both savings and excess P remaining. As the costs for non-transportation aspects of manure application increases, the flexibility between savings and excess P remaining decrease and a single solution becomes optimal for both objectives.

4.2.5 Scenario 4: Optimal Manure Redistribution with Constraints on Net Costs for each Individual Trip Using Historical Fertilizer Prices

It is often found that transporting manure cannot be profitable beyond short distances (Paudel et al., 2009; Sharpley et al., 2016). However, the results in Figures 5 and 6 paint a very different picture since the distances travelled can exceed 100 km and still provide savings compared to using fertilizer. One key reason that results in this study are different is recent increases in the price of fertilizer. In 2002 the price of ammonium nitrate fertilizer was $195/ton and by 2012 it had hit $506/ton. Phosphorus fertilizer saw a similar cost increase, moving from $221/ton to $665/ton. This significant increase in cost means that using manure in place of fertilizer is much more feasible in many parts of the country.

In order to examine the effect the change in fertilizer prices had on the ability to transport manure, Optimization Formulation 1 was solved using the fertilizer costs for 2002 and 2012 (Figure 7).

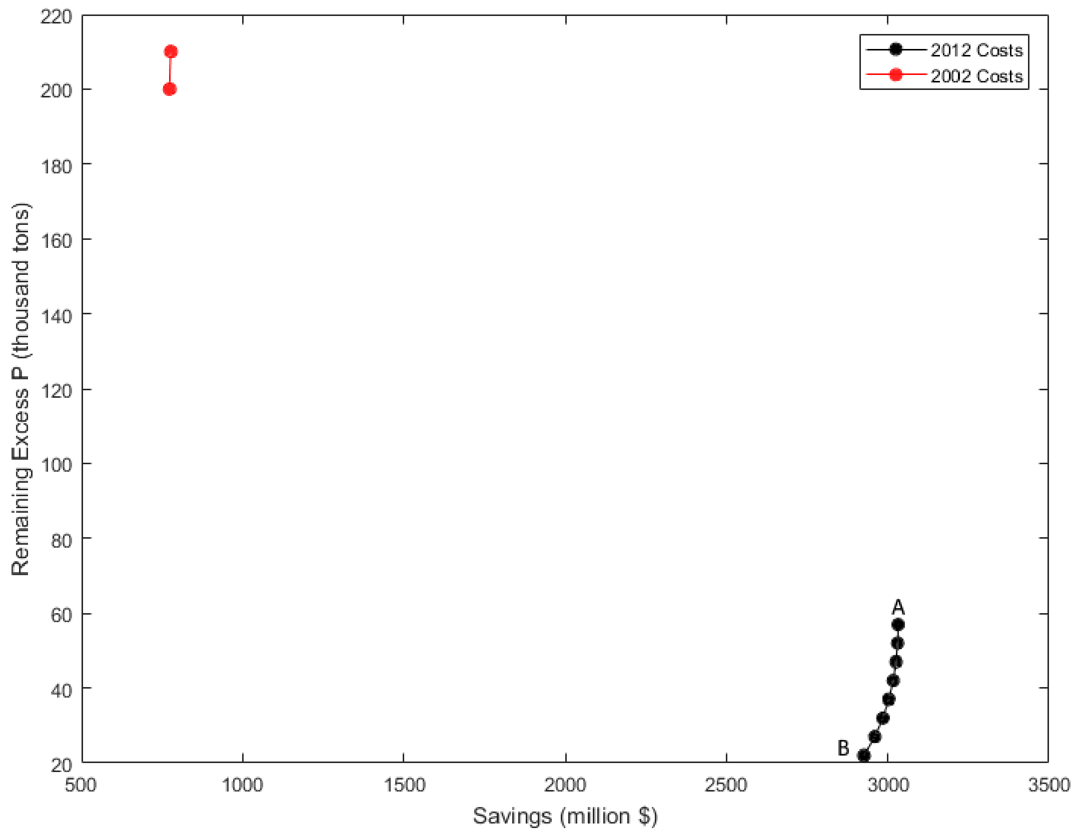

Figure 7. Trade-off curve between cost savings and remaining excess P within CONUS with fertilizer costs for different years. The 2012 cost curve is the T = 1 curve from Figure 6. Both the curves were done with a value of T = 1 for transportation restrictions.

Manure transportation using 2002 fertilizer prices resulted in a significantly worse results for both optimization parameters, savings and excess P remaining. The 2002 results transported 35% less P and had 72% less savings.

4.2.6 Scenario 5: Optimal Manure Redistribution with and without Constraints on Net Costs for Each Individual Trip

After solving Optimization Formulation 1 for the contiguous United States, the same problem was solved for the state of California. In addition to the values of f used previously, Optimization

Formulation 1 was also solved for when T = 0. This was done to see how significantly the restrictions on transport distances affected the solution at the system level. The results of these solutions to Optimization Formulation 1 can be seen in Figure 8.

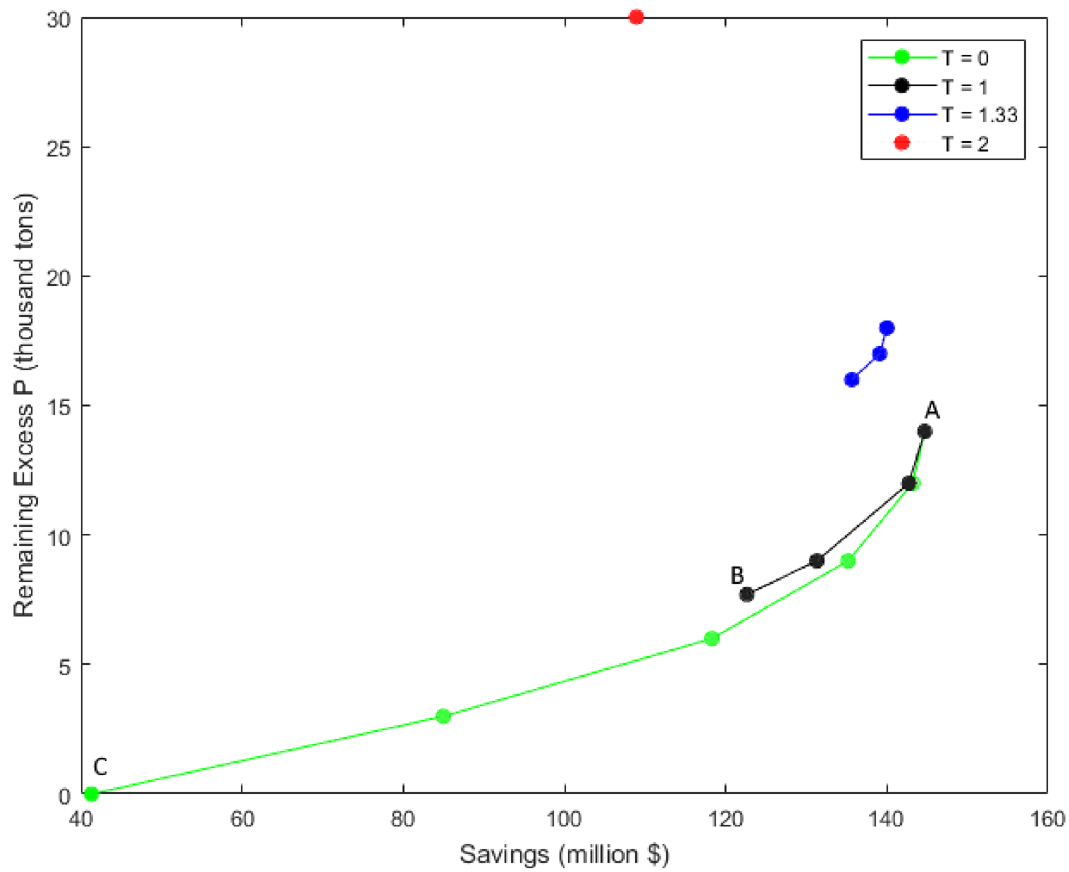

Figure 8. Trade-off curve between cost savings and remaining excess P within California with varying cost restrictions. The lines for T = 1, T = 1.33, and T = 2 represent solving Optimization Formulation 1 with the same restrictions as the solutions in Figure 6. The line for T = 0 shows how the solution would change when all restrictions on transportation distance are removed. Solution C is the result when transporting all of the excess phosphorus without restrictions on distance.

This smaller area allows for a comparison of the restricted transport scenarios shown in Figure 8 to a scenario where there are no restrictions on transport distances. The curves for T = 1, T = 1.33, and T = 2 behave like how they did in Figure 6. On the right edge of the curve, the unrestricted transport curve reaches the same optimum savings point as the T = 1 curve did. They reach the same point because the maximum savings when T = 1 is the global optimum point for maximizing savings. When moving from T = 1 to T = 0, no additional ways to increase savings are added to the optimization formulation. Differences between the two solutions start to show up as more P is transported. As the amount of P transported increased, the rate of decrease for the savings was slower for the T = 0 curve than the T = 1 curve. This difference reached 3% greater savings by the end of the T = 1 curve. After reaching that point, the unrestricted curve continued to reduce the amount of excess P at increasing costs. As the crop demand in California is greater than the P production, the unrestricted transportation curve eventually reached a point where no excess P was remaining. Moving from the maximum P reduction on the T = 1 curve to no excess P remaining on the unrestricted transport curve reduced the savings by 82 million dollars (52% reduction).

4.3 Ability of Biogas Plants to Utilize Excess Manure

Transporting manure with distance restrictions was able to utilize the vast majority of the excess P in CONUS, but 22,000 tons of excess P still remained after transporting as much as possible. This section examines scenarios where biogas plants are built in order to use the remaining manure. Two different scenarios were explored in order to examine the costs and benefits of building and operating biogas plants. Scenario 6 uses Optimization Formulation 2 to examine the benefits of building biogas plants after manure transportation in CONUS. Scenario 7 then examines the difference between building biogas plants after manure transportation and doing both manure transportation and biogas plant construction at the same time, using both methods to maximize overall savings.

4.3.1 Scenario 6: Optimal Biogas Plant Construction Following Manure Redistribution

There is still excess P present after transporting manure for use as fertilizer, although the amount was greatly reduced. A method of further reducing the amount of excess P is by building and operating biogas plants that use manure. The solution shown at point B in Figure 4 was used as the initial conditions to examine the use of biogas plants in reducing excess P after the transportation solution. From this point, Optimization Formulation 2 was solved in order to find the maximum profit from biogas plants. This resulted in an increase in the system savings of $99 million dollars, bringing the total annual system savings after both manure transportation and biogas plant construction to $3,024 million dollars. This solution also resulted in a complete removal of all the excess P in the system. The result of this can be seen in Figure 9.

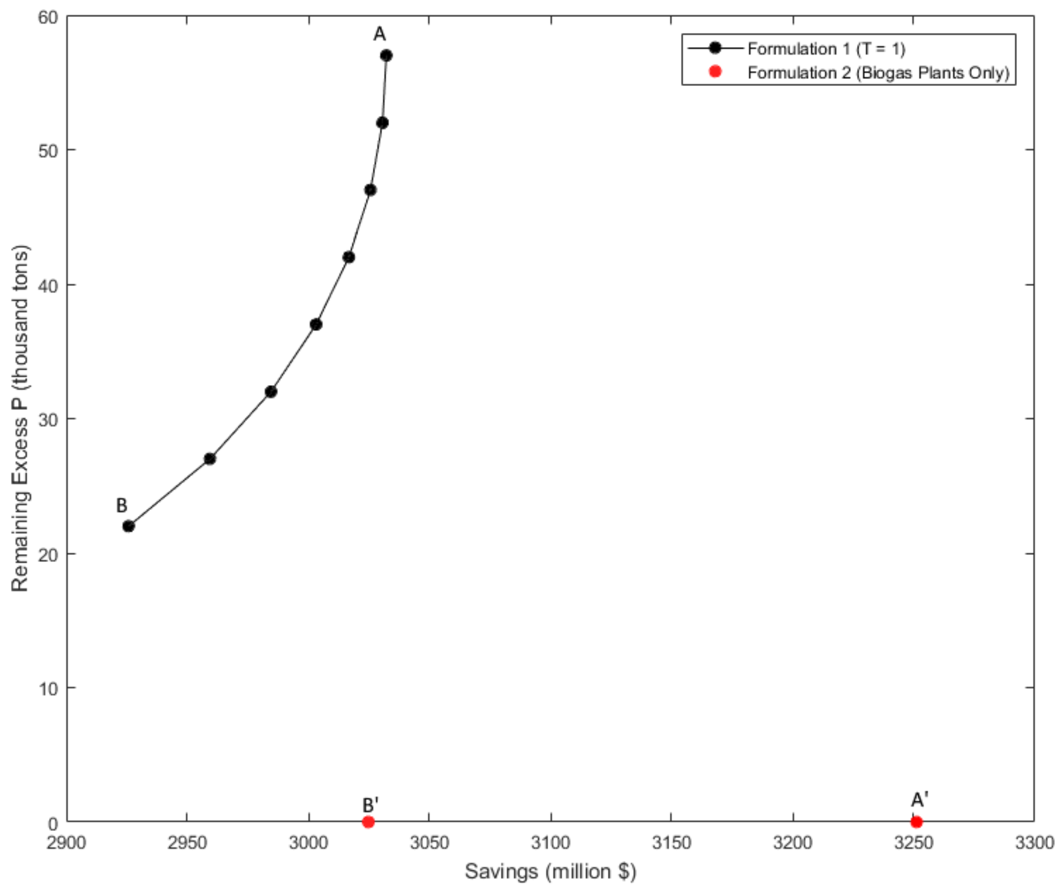

Figure 9. Trade-off curve between cost savings and remaining excess P within CONUS with for manure transportation and the change in cost savings and excess P when constructing biogas plants after manure transportation. The trade-off curve shown is the curve for when T = 1 from Figure 6. The biogas solution was then found by maximizing for profit using Optimization Formulation 2. Point A' denotes the solution to Optimization Formulation 2 when using the solution at point A as the initial condition and point B' denotes the solution to Optimization Formulation 2 when using the solution at point B as the initial condition.

The solution at point B' in Figure 8 resulted in 387 plants being built and processing 12 million tons of manure. These biogas plants produce a total of 2.56 TWh of energy each year and make an average profit of $250 thousand dollars each.

The locations of the biogas plants were highly concentrated in a few locations across CONUS. As all of the excess P in Region 2 was used in Scenario 2, there were no biogas plants located in that region. Additionally, Regions 1 and 3 had significantly fewer plants than Region 4 since most of the manure in these regions was also used in Scenario 2. In addition to having the most biogas plants, Region 4 also had the largest plants. The mean biogas plant in Region 4 uses 32,900 tons of manure each year, 45% higher than the mean from the other regions (Table 9).

Table 9. Proposed biogas plants, including associated costs and benefits, Scenario 5. Under this scenario, I assume that excess manure has already been transported and spread under the net zero-cost constraint cost scenario. Results presented here are based on the assumption of a maximum plant size of 100,000 tons of manure per year.

Region	Number of Biogas Plants	Mean Biogas Generation (ft3/day)	Mean Annual Income From Energy Generation (USD)	Estimated Mean Annual Transport Costs (USD)	Net Profit (USD)
USA	**387**	**559,142**	**678,939**	**27,185**	**99,201,903**
Northeast	**52**	**431,614**	**524,088**	**980**	**11,101,092**
New England	46	454,891	552,353	669	10,415,023
Middle Atlantic	6	253,155	307,394	3,369	686,069
Midwest	**0**	**0**	**0**	**0**	**0**
East North Central	0	0	0	0	0
West North Central	0	0	0	0	0
South	**23**	**362,987**	**440,758**	**3,406**	**4,006,656**
South Atlantic	18	448,883	545,057	1,895	3,993,822
East South Central	0	0	0	0	0
West South Central	5	53,762	65,281	8,842	12,834
West	**312**	**594,856**	**722,306**	**33,306**	**84,108,164**
Mountain	216	388,629	471,894	14,120	38,235,689
Pacific	96	1,058,868	1,285,732	76,474	45,872,475

The majority of the biogas plants were located within a few states. In Region 4, where most of the biogas plants were located, most of the biogas plants were located in New Mexico, Arizona, and California, with some locations in Idaho and Washington. This concentration is also true in the other regions. In Region 1 the biogas plants were concentrated in Vermont and Maine, while in Region 3 the biogas plants were located in North Carolina and Virginia. This can be seen in Figure 10.

These results suggest that many more biogas plants are financially feasible than just the currently active ones, as these plants produce a significant profit despite using less than 10% of the total manure produced in the United States each year.

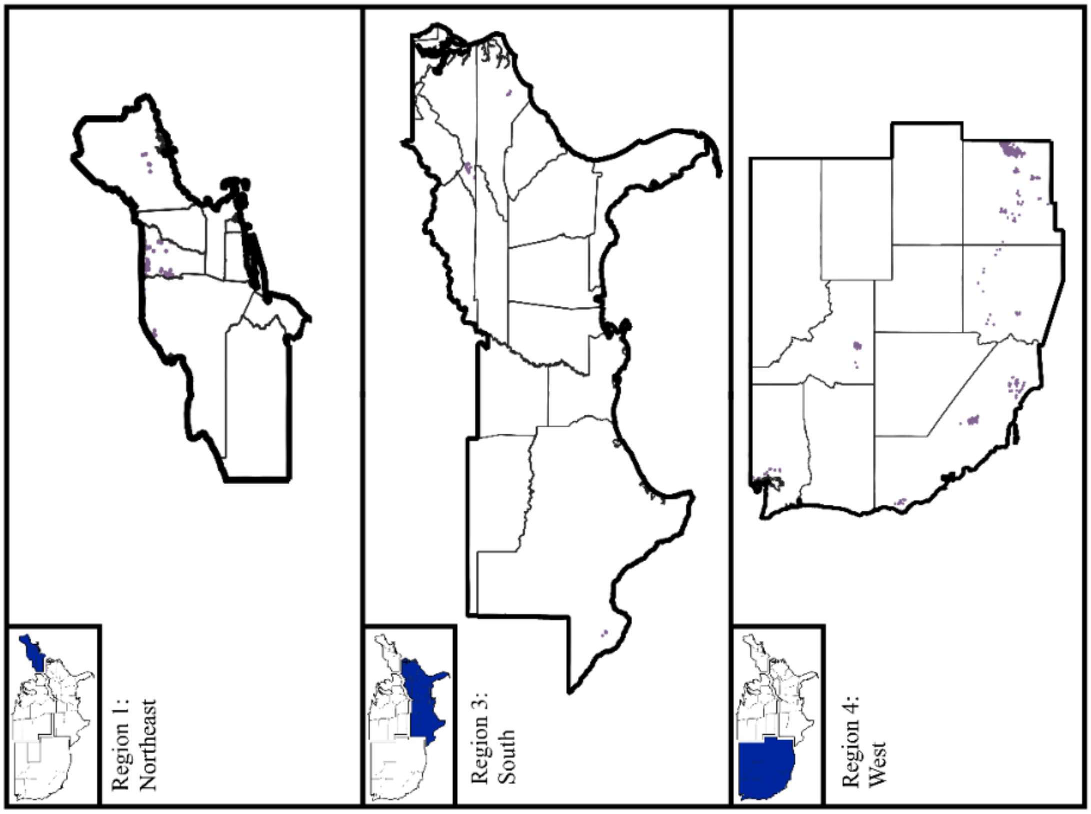

Figure 10. Biogas plants built in solution B from Figure 8 in each region of the United States. Region 2 was omitted because no biogas plants were located in that region.

4.3.2 Scenario 7: Optimal Biogas Plant Construction with Simultaneous Manure Redistribution

After solving Optimization Formulation 2 for the contiguous United States, the same problem was solved for the state of California. Like in the CONUS solution, the Optimization Formulation 2 was solved using the results from Optimization Formulation 1 with the least remaining excess P when T = 1 as the initial conditions. Solving Optimization Formulation 2 in California gave a similar result as for CONUS, where the excess P was able to reach 0 and produced profits (Figure 11).

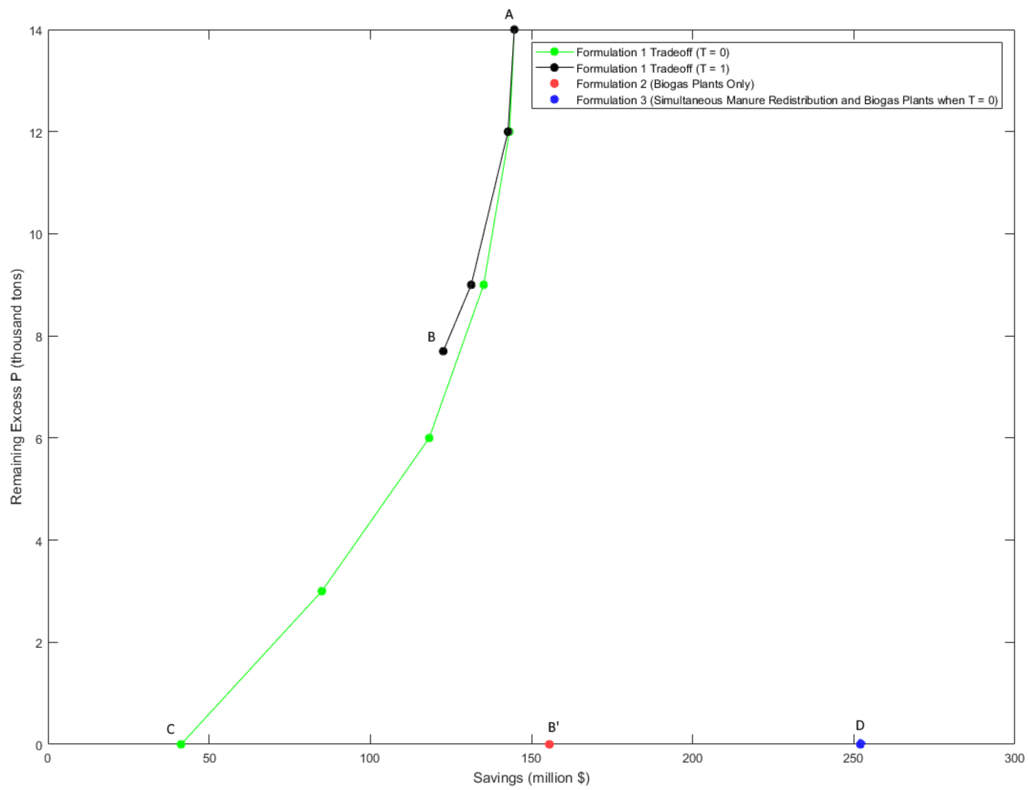

Figure 11. Trade-off curve between cost savings and remaining excess P within California. The tradeoff curve is the result for T = 1 (manure redistribution constrained so that benefits are greater than costs for each trip) from Figure 8. The solution B' was found with Formulation 2 using the phosphorus balance from solution B as the initial conditions. Solution D is made by solving Optimization Formulation 3, which includes both the transportation and biogas components and solves for them simultaneously.

The second solution done in California was for Optimization Formulation 3. This solution was for simultaneous solving of transportation for fertilizer when T = 0 and using the manure in biogas plants. This solution reduced the excess P to 0 and had savings of $252 million dollars. This solution had significantly higher savings than the previous solutions where manure use as fertilizer was prioritized. This suggests that, if maximizing savings were the primary goal, it may be more effective to prioritize constructing biogas plants instead of transporting much of the manure for fertilizer.

4.4 Summary of Key Findings

My first objective was to examine the degree of coupling between manure produced and crop nutrient requirement. When examined at a 6 km x 6 km grid scale, I found that the phosphorus balance between livestock and crop locations is decoupled. Despite a national crop P uptake of more than double the manure P production, 530,000 tons (54%) of manure P is located in a cell where, if applied, it would exceed the crop P uptake in that cell. Due to this, manure P is only able to meet 22% of the phosphorus needs of crops in the United States within the cell it originates in. If the rest of the manure were transported to a cell where it could be applied as fertilizer, another 26% of the crop P uptake could be met by recycling P from manure. This conclusion is similar to MacDonald et al. (2012), who found that changes in farm management could cut P fertilizer requirements by 44%.

Transporting this excess manure P to use in a cell that requires additional crop P fertilizer was found to both reduce the amount of excess phosphorus from manure in grid cells and provide savings through a reduction in the amount of mineral fertilizer needed to be purchased. It was found to be possible to transport all of the excess manure with a system savings of $2.3 billion USD. However, 8% of all such manure redistribution trips were economically infeasible (e.g., they lost money) due to the distances manure needed to be transported in order to reduce the excess phosphorus to 0 across the entire continental US. Local scale management of manure redistribution would be unlikely to involve trips that were not economically beneficial. Reflecting this reality, results showed that when optimizing for savings while preventing trips that lose money, 88% of the excess manure P was still able to be transported with a total system savings of $3 billion USD.

My results show that manure transport can be a net profit in the United States, unlike what Akram et al. (2019a) found for Sweden. This difference is most likely due to the difference in distance that manure needs to be transported. Akram et al. (2019a) had a mean transport distance of 202 km, while solutions derived here had much smaller mean transport distances (e.g., solution A in Figure 5 has a mean transport distance of only 38 km). This shorter distance is largely due to differences in the location of manure sources relative to cropland and the relative magnitude of manure P production and crop P demand in Continental US versus Sweden. In Sweden most of the manure production is in the northern and southern areas of the country and the crop P is in central Sweden, while in US there is the Midwest belt of demand, but livestock surrounds it. Additionally, the difference in spatial resolution may also contribute to the difference, as Akram et al. (2019b) first focused results on the district scale and found that increasing the resolution may be able to decrease the cost of transportation. For example, in the Midwest the mean transport distance is 15 km, while the distances between counties range from 20 – 100 km. Thus, if we did the analysis at the county scale, we would never be able to achieve transport distances less than the minimum county centroid distance

As the primary financial benefit from transporting manure is a reduction in mineral fertilizer purchases, transporting manure becomes more attractive as mineral fertilizer becomes more expensive. This was demonstrated by comparing the benefits of redistributing manure when fertilizer costs are for 2012 ($665/ton P fertilizer) to the benefits of redistributing when fertilizer costs are from 2002 ($282/ton P fertilizer) (USDA-NASS, 2016). Using fertilizer costs from 2012 allowed for nearly 50% more manure to be transported and over $2 billion USD in additional benefits over the US. Mineral fertilizer demands are expected to keep increasing (Bouwman et al., 2013; Godfray et al., 2010), and the prices that come with this will seemingly make the redistribution of manure for fertilizer become even more attractive over time.

The construction and operation of biogas plants was found to be a viable alternative to redistributing manure as fertilizer in cases where manure redistribution was economically infeasible or impractical. The annualized profits for a biogas plant were estimated to be $-19466 + $9.80 per ton of manure, resulting in the potential for plants to be profitable when processing at least 2000 tons of manure per year. This does not take into account transport costs, which would increase the size a biogas plant would have to be before becoming profitable. When solving the optimization formulation to maximize biogas plant profits, the biogas plants showed significant profits. Using the results from the manure redistribution as the initial conditions (e.g., more limited amounts of excess manure remaining in various cells), siting 387 biogas plants reduced the excess P application from 22,000 tons to 0 tons while producing profits of $99 million USD. Due to computational limitations, the national scale solution was restricted to optimizing the biogas plants after manure redistribution for fertilizer, but the smaller scale simultaneous manure transportation for fertilizer and biogas plants also showed promising results. In California, solving with both manure management possibilities simultaneously resulted in an increase in the amount of manure used in biogas plants and a decrease in the amount of manure used for fertilizer and produced an increase in savings across California of approximately 100 million USD (a 67% increase in savings relative to the sequential solution approach).

Chapter 5 – Conclusions

Global food demand is increasing and the amount of nitrogen and phosphorus fertilizer required to meet these demands is increasing as well. At the same time, concerns about the long term availability of mineral phosphorus for fertilizer use have also increased. Increasing spatial disconnects between livestock operations and cropland has also led to over application of livestock manure on land nearby to livestock operations and the subsequent runoff of nutrients in the manure. Effectively applying manure to meet crop requirements is an effective way to recycle manure and reduce mineral fertilizer demand, if the manure can be moved to a location where it is needed.

The first objective of this study as to quantify the crop P demand and the manure P available across the United States. I found that there was 2,040,000 tons of crop P uptake and 980,000 tons of manure P production in 2012, with 450,000 tons of the manure able to meet demand within the grid cell (6 km x 6km) it started in. This met 22% of the crop P requirements, with an additional 26% able to be met if the manure was moved to the correct grid cells. All of the regions had higher crop P requirements than manure P production, although there was spatial disconnects between the locations of each in all four regions. The Midwest had the highest amount of crop P demand and manure P production while the Northeast had the lowest of both.

The second objective was to examine the costs and benefits of manure transportation to meet crop phosphorus demand and then optimize the transport to maximize the benefits. The distance that manure was able to be transported was based on the cost of transport and the price of mineral fertilizer. Dairy cow manure had the lowest phosphorus content and was the manure least able to be transported while poultry manure had the highest phosphorus content and was the most able to be transported. Transporting all of the excess manure from where it started to a location where it could be used was possible and created a total estimated benefit of $2,345 million USD. However, 8% of the trips in this simulation cost more to transport manure than the benefit from reduced fertilizer costs. The losses were particularly large in New England, where 61% of trips lost money.

There were fewer losses in the Midwest region, where < 1% of all trips lost money when transporting manure.

An optimization model was built in order to maximize the benefits from transportation and remove the individual losses. This model resulted in an estimated total benefit of $3,013 million USD, an increase of 28% over the initial model. However, the amount of manure able to be transported was also reduced by 52,000 tons. Increasing the amount of manure transported resulted in an increased 30,000 tons being transported and a reduction in total benefits of $105 million USD. The total benefit increase when not restricting individual losses was found to be around 3% when using a single state as a small scale test case.

The third and final objective was to examine the costs and benefits on biogas plant construction and operation when using manure as a fuel source and then optimize the profits of the biogas plants. The profits of the biogas plants were annualized assuming a 20 year lifetime and calculated as a function of the size of the biogas plants. The profits associated with biogas plants were $-19466 + $9.80 per ton without including transportation costs. This result means that biogas plants that process less than 2000 tons of manure a year are not profitable. This number may be even higher when after taking transportation costs into account.

An optimization model was built in order to maximize the profits of the biogas plants. The optimization model used the calculated profits from running biogas plants and the transportation costs calculated during the previous objective in order to maximize the overall profit. The model was solved for CONUS using the solutions from the manure transportation as the initial conditions. Solution A' identified 1077 locations to build biogas plants and these used all of the 52,000 tons of remaining excess phosphorus from Solution A in Scenario 3 and produced a profit of $219 million USD. Solution B' used Solution B from Scenario 3 as its initial conditions and had 22,000 tons of excess phosphorus before solving Formulation 2. Solution B' reduced the excess phosphorus to 0 by building 387 biogas and produced a profit of $99 million USD. Using a single state as a test case, biogas plant construction was run simultaneously with manure transport for fertilizer. In this case, the majority of the manure was used in biogas plants while only a small fraction of the manure was transported to fulfil crop P demands.

5.1 Recommendations for Future Work

This study quantified the crop P demand and the manure P supply across the United States at a 6 km x 6 km scale. It then quantified the costs and benefits of transporting the excess manure as for use as fertilizer and optimizing the benefits associated with it. Finally, it quantified the costs and benefits of using the excess manure as fuel for biogas plants and optimizing the profits associated with it.

An extension of this work would be to fully analyze the environmental impact of the optimization solutions. First, the reduction in excess phosphorus application would have an impact on the quantity of nutrients entering the aquatic ecosystem. Second, both manure transportation as fertilizer and biogas plant operations will have an effect on GHG emissions. Truck transport of manure increases GHG emissions, while biogas plant operations decrease GHG emissions from manure and replacing fertilizer with manure will decrease GHG emissions from fertilizer production. Quantifying both of these effects will more accurately show the environmental impact of the optimization solutions.

Another extension of this work would be to further integrate the optimization models used in this study. Due to computation limitations, biogas plant location analysis was run following manure transportation for fertilizer across CONUS (e.g., two sequential optimization problems), but the small test case of simultaneous optimization in California suggests that a significant amount of the manure in the country would be more profitable being used in biogas plants. Solving the simultaneous optimization formulation at the national scale would likely generate substantially higher additional savings since California results indicate savings increased by 67%. Additionally, biogas plants produce a by-product slurry that is high in phosphorus. Including the application potential of this P source would also potentially increase profits and further increase phosphorus recycling.

A final extension of this work would be to create a grid-scale nitrogen balance across CONUS and use this as a constraint in the optimization problems as well. It is well known that crop P requirements are generally met before crop N requirements when applying manure, but this addition would allow the benefits from the nitrogen in the manure to be more accurately quantified and optimized for (Kellogg et al., 2000).

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Appendix A – Accompanying Data

Files contained in linked file:

p_bal_initial.zip: Shapefile of the initial phosphorus balance

p_bal_post_transport.zip: Shapefile of the results of Scenario 3

biogas_locations.zip: Shapefile of the results of Scenario 6

Scenario_1_2_prep.m: Matlab file used to prepare datasets for Scenarios 1 and 2.

Scenario_1_run.m: Matlab file used to run the algorithm used in Scenario 1.

Scenario_2_run.m: Matlab file used to run the algorithm used in Scenario 2.

Formulation1.mod: OPL model file used to optimize Formulation 1.

Formulation1.ops: Settings file used alongside Formulation_1.mod.

Formulation2.mod: OPL model file used to optimize Formulation 2.

Formulation3.mod: OPL model file used to optimize Formulation 3.

Formulation2_3.ops: Settings file used alongside Formulation2.mod and Formulation3.mod.

Manure_P.xlsx: Excel file containing the phosphorus inputs from each category of livestock and the summation of these inputs for each cell.

P_Balance.xlsx: Excel file containing the total manure phosphorus inputs, crop phosphorus requirements, and difference between the two values for each cell.

Scenario_1_2_Inputs.mat: Matlab file containing all the required inputs for Scenario 1 and 2.

Scenario_1_Results.mat: Matlab file containing all the results data from Scenario 1.

Scenario_2_Results.mat: Matlab file containing all the results data from Scenario 2.

Scenario3T1.dat: Data file used when solving Formulation 1 for Scenario 3 when T = 1.

Scenario3T133.dat: Data file used when solving Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T2.dat: Data file used when solving Formulation 1 for Scenario 3 when T = 2.

Scenario4.dat: Data file used when solving Formulation 1 for Scenario 4.

Scenario5T0.dat: Data file used when solving Formulation 1 for Scenario 5 when T = 0.

Scenario5T1.dat: Data file used when solving Formulation 1 for Scenario 5 when T = 1.

Scenario5T33.dat: Data file used when solving Formulation 1 for Scenario 5 when T = 1.33.

Scenario5T2.dat: Data file used when solving Formulation 1 for Scenario 5 when T = 2.

Scenario6A: Data file used when solving Formulation 2 for Scenario 6 when using Point A from Figure 6 as the initial conditions.

Scenario6B: Data file used when solving Formulation 2 for Scenario 6 when using Point B from Figure 6 as the initial conditions.

Scenario7Formualtion2.dat: Data file used when solving Formulation 2 for Scenario 7 when using Point B from Figure 7 as the initial conditions.

Scenario7Formulation3.dat: Data file used when solving Formulation 3 for Scenario 7.

Scenario3T1 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 3.txt: Text file containing the third solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 4.txt: Text file containing the fourth solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 5.txt: Text file containing the fifth solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 6.txt: Text file containing the sixth solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 7.txt: Text file containing the seventh solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T1 – 8.txt: Text file containing the eighth solution to Formulation 1 for Scenario 3 when T = 1.

Scenario3T133 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T133 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T133 – 3.txt: Text file containing the third solution to Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T133 – 4.txt: Text file containing the fourth solution to Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T133 – 5.txt: Text file containing the fifth solution to Formulation 1 for Scenario 3 when T = 1.33.

Scenario3T2 – 1.txt: Text file containing the solution to Formulation 1 for Scenario 3 when T = 2.

Scenario4 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 4.

Scenario4 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 4.

Scenario5T0 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T0 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T0 – 3.txt: Text file containing the third solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T0 – 4.txt: Text file containing the fourth solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T0 – 5.txt: Text file containing the fifth solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T0 – 6.txt: Text file containing the sixth solution to Formulation 1 for Scenario 5 when T = 0.

Scenario5T1 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 5 when T = 1.

Scenario5T1 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 5 when T = 1.

Scenario5T1 – 3.txt: Text file containing the third solution to Formulation 1 for Scenario 5 when T = 1.

Scenario5T1 – 4.txt: Text file containing the fourth solution to Formulation 1 for Scenario 5 when T = 1.

Scenario5T133 – 1.txt: Text file containing the first solution to Formulation 1 for Scenario 5 when T = 1.33.

Scenario5T133 – 2.txt: Text file containing the second solution to Formulation 1 for Scenario 5 when T = 1.33.

Scenario5T133 – 3.txt: Text file containing the third solution to Formulation 1 for Scenario 5 when T = 1.33.

Scenario5T2 – 1.txt: Text file containing the solution to Formulation 1 for Scenario 5 when T = 2.

Scenario6B – Build.txt: Text file containing the solution to Formulation 2 for the variable *y* for Scenario 6 when using Point B from Figure 6 as the initial conditions.

Scenario6B – Transport.txt: Text file containing the solution to Formulation 2 for the variable *z* for Scenario 6 when using Point B from Figure 6 as the initial conditions.

Scenario7Formulation3 – Biogas_Build.txt: Text file containing the solution to Formulation 3 for the variable *y* for Scenario 7.

Scenario7Formulation3 – Biogas_Transport.txt: Text file containing the solution to Formulation 3 for the variable *z* for Scenario 7.

Scenario7Formulation3 – Manure_Transport.txt: Text file containing the solution to Formulation 3 for the variable *x* for Scenario 7.